TRANSISTORS

in Radio and Television

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II

PREFACE

In the short space of eight years, the transistor has climbed from the level of a laboratory curiosity to the stature of a highly competitive commercial product. When the scientific history of the present century is completed, it will undoubtedly be found that the transistor stands high on the list of outstanding achievements. For if we consider the vacuum tube as man's first significant advance into the field of electronic communications, then the transistor must certainly be heralded as man's second most important step.

The scope of transistor application is as wide as engineering ingenuity. Already, this remarkable speck of solid matter has usurped the role of the vacuum tube in electronic equipment from miniature pocket radios to ceiling-high computers. There is no segment of the electronics field in which it cannot or will not be used, and it is necessary that everyone who has any interest in this field become intimately acquainted with this amazing device.

This book is written for radio and television technicians and all other technical workers who desire to gain a working knowledge of transistors and transistor circuits. The discussion starts with modern electron theory and then progresses to the operation of point-contact, junction, and other transistors. This is followed by four chapters in which a variety of transistor circuits are analyzed, particularly those which are used in radio and television receivers. All circuit explanations employ the highly successful step-by-step approach, starting with the simplest facts and proceeding gradually to the more complex. No mathematics of any difficulty is used in the text.

In Chap. 8, recent transistor developments of importance are analyzed, revealing how these transistors operate. In Chap. 9, there is a discussion of the various precautions to observe when servicing transistor circuits and transistor devices. A method of approach to the servicing of all such units is also given. In Chap. 10, a series of simple and easily worked transistor experiments are included for those readers

who may wish to learn of transistor operation firsthand. To the practical man, this is valuable experience.

The book can be used in technical institutes, radio and television schools, colleges, high schools, training programs in electronics, or for home study. Questions are included for each chapter, to be used by an instructor to test the progress of a student or as a form of self-test for those studying alone. An extensive bibliography at the end of the book is available for those readers who would like to read the fascinating story of transistor development in full as it is unfolded by the men who pioneered its research. With these articles, additional references will be found leading to material of almost any desired complexity and detail.
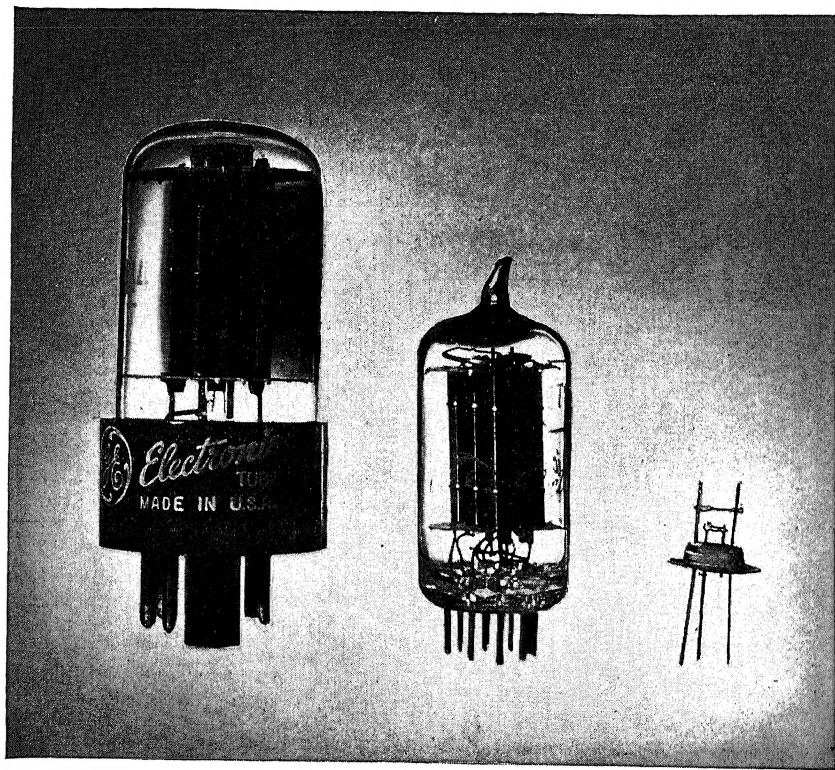
The author wishes to extend his appreciation to the many companies in this field, among them CBS-Hytron, Radio Corp. of America, Minneapolis-Honeywell Regulator Co., General Electric Company, Philco Corporation, and *Electronics* magazine for the data and material which they so graciously provided. The author is also indebted to Melville Byron of the Precise Development Corp. for his aid in supplying valuable transistor information.

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Comparison of a regular vacuum tube (left), a miniature vacuum tube (center), and a transistor (right), shown actual size. (*Courtesy General Electric Company.*)

INTRODUCTION TO MODERN
ELECTRON THEORY

Introduction. The story of the transistor is, in large measure, the story of matter and how the scientists at the Bell Telephone Laboratories have been able to make that matter amplify electrical currents. If the transistor served no commercial end, it would still be important for its contribution to our understanding of matter in the solid state. It demonstrated, for the first time in history, that man could achieve amplification in a solid, a feat which heretofore could be accomplished only by using vacuum tubes. If we consider the vacuum tube as man's first significant advance into the field of communications, then the transistor must certainly be heralded as man's second most important step. For here, surely, is as radical a departure from what has heretofore been done as the discovery of the triode by Dr. Lee De Forest in 1906.

The discovery of the transistor is officially credited to John Bardeen and W. H. Brattain, two scientists working for the Bell Telephone Laboratories. The first public announcement of the transistor was made in June, 1948. Thus, in terms of time, the transistor is barely out of its infancy. In terms of application, however, it cannot be classed far behind the vacuum tube. And while there is no imminent prospect that it will completely replace the vacuum tube, the transistor has nevertheless made serious inroads in a field that was once exclusively the province of the vacuum tube.

The most obvious attractions of transistors lie in their higher operating efficiency and smaller size than comparable electron tubes. A transistor, being a solid, requires no special envelope surrounding a vacuum; furthermore, it requires no filament heating element to serve as the provider of electrons. The latter fact alone represents a considerable saving in power, since in most standard receiving tubes, as much or more power is expended frequently in heating the filament as in drawing current through the tubes. For example, in a 6CB6, the filament

requires a current of 0.3 amp at an applied voltage of 6.3 volts. This represents a power dissipation of 6.3 × 0.3, or 1.89 watts. For typical operation as an amplifier, plate current is about 9.0 ma when the plate voltage is 200 volts. The power dissipated in this circuit is equal to 200 × 0.0090, or 1.8 watts. Elimination of the filament would reduce the over-all power needs of this amplifier by half. Actually, in most applications, the power saving is greater than this because of the higher efficiency of the transistor. Add to this a volume which is on the order of one-thousandth that of a vacuum tube and a weight which is reduced by a factor of 100 and the attractiveness of the transistor becomes quite evident.

Operation of vacuum tubes depends upon the flow of electrons from filament to plate and the control of this flow by intermediate grids. Operation of the transistor is also largely dependent upon an electronic flow, although there are considerable differences between the two units. In order to appreciate these differences, it is best to review what we know concerning the structure of matter and the role the electron plays in that structure.

ATOMS AND MOLECULES

Every substance or material that we come in contact with or which is known to man can be divided ultimately into particles known as molecules. These are the smallest segments into which a substance can be divided and still retain all its individual characteristics. Molecular units are so minute that we have not been able to devise instruments which will enable us to see them, and it is doubtful that we ever shall. In order to see something which is extremely small in size, we must design an instrument, such as an optical microscope or electron microscope, which will detect this "something" and then enlarge it so that we, with our gross eyesight, shall be able to see it. However, every instrument we use is, itself, composed of molecular building blocks. How could we then distinguish between the molecules of the substance we are checking and the molecules of the instrument? Thus, although it is unlikely that we shall ever see a direct picture of a molecule, highly refined indirect methods have been developed for determining molecular structure so that we know quite a bit about it.

We know, for example, that the molecule of a substance may consist of a single element of nature or a complex association of a number of elements. Chemists and physicists have discovered over a period of hundreds of years that there are something like 101 different elements which, either singly or in combination, make up all the matter on this

planet. This figure of 101 is not a static one but has gradually been raised as man's knowledge and scientific know-how have broadened. Although it is unlikely that the number of elements will expand much more, this may occur. At any rate, the number has been close to 100 (i.e., in the nineties) for many years and will suffice for our study here. The elements which are most familiar are hydrogen, oxygen, gold, silver, nickel, copper, iron, etc. Molecules of elements can be further subdivided into smaller particles, but when we do this, the elements no longer retain their distinctive characteristics.

Each molecule of silver contains only this element. On the other hand, a water molecule is composed of two elements, hydrogen and oxygen. Thus, for compounds containing several elements, we apply only the word molecule; however, where a substance is composed of a single element, either designation, molecule or element, may be used. In general, most substances are combinations of elements and, frequently, fairly complex combinations. Single-element substances are less common.

Another name that is linked with element is atom, and for the most part the two may be considered as one and the same thing. However, those who have studied chemistry or physics know that an element may have several atoms, each possessing a slightly different atomic weight. For example, there is an ordinary hydrogen atom (atomic weight 1.008) and a heavy hydrogen atom (atomic weight 2.015), which is sometimes called deuterium. Chemically, both hydrogen atoms react alike. But a quart of water made with ordinary hydrogen atoms will weigh less than a quart of water made using heavy hydrogen.

What is true of hydrogen is true of many other elements; that is, each of these elements has more than one type of atom. A special name has been given to all the different atoms of an element; this name is isotopes. As a general definition, isotopes of an element have the same chemical properties but differ in mass. Thus, while this distinction is of small significance to us in our study of transistors, still a difference does exist, the word element being a somewhat more general term than atom.

ATOMIC STRUCTURE

Thus, as we tread our way down the scale of size, we come first to molecules and then to elements and atoms. When we investigate the last, we find that they consist of a centrally situated nucleus with a net positive charge, surrounded by a number of electrons which revolve about the nucleus. The central positive charge is said to be due to

protons, while the electrons have a negative electrical charge. In a stable atom, the positive charge of the nucleus is exactly counterbalanced by the negative charge of the externally revolving electrons. The net electrical charge is zero, and this is the conventional state of most atoms.

The atom possessing the simplest structure is hydrogen. It consists of a positive nucleus containing a single proton. Revolving around this proton is a single electron. The illustration most commonly employed for the hydrogen atom is shown in Fig. 1. Actually, we have learned enough about atomic structure to know that Fig. 1 is a highly simplified picture of the hydrogen atom. However, we would not gain any greater understanding of transistor action by modifying this illustration to conform to more recent theories, and its simplicity does impart an understanding that might not be obtained otherwise. Hence we shall remain with this, the more classic method of representation.
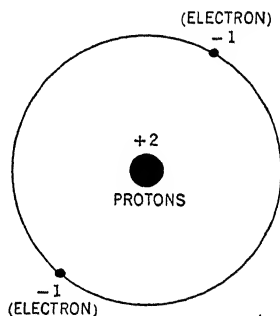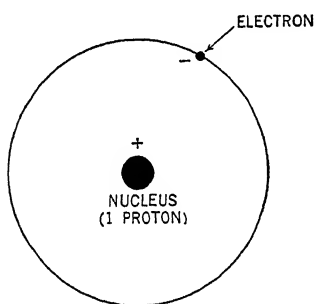
FIG. 1. The structure of a hydrogen atom.   FIG. 2. The atomic structure of helium.

Helium follows next in order of complexity, and its atomic structure is indicated in Fig. 2. The central positive charge is 2, indicating two protons, and this charge is offset by having two electrons rotating about the nucleus. Each element then follows in numerical turn, with the central positive charge increasing in steps of 1 and being electrically counterbalanced by additional electrons revolving in paths or orbits about the nucleus. It can be appreciated that the nucleus and the associated electrons soon attain a highly complex structure.

The electrons which revolve about the nucleus do not follow random paths; rather they fall into definite energy levels. These levels may, for simplicity, be visualized as shells, each successive shell being spaced at a greater distance from the nucleus. The shell, or energy level, closest to the center carries a single electron (as in the hydrogen

atom) or two electrons (as in helium and all other atoms). These electrons may rotate at any angle about the nucleus, but they are more or less bound to remain within the confines of the shell.

When we reach the third element, lithium, we find that the nucleus has a positive charge of 3, which is electrically counterbalanced by 3 negative electrons revolving around the nucleus (see Fig. 3). Two of the electrons revolve about the center within the boundaries established by the energy level, or shell, just mentioned for the hydrogen and helium atoms. The orbit of the third electron, however, is much farther removed from the nucleus, and it may be said to operate within another level which is entirely distinct from that of the first shell. This second level has been found capable of holding up to a maximum of 8 electrons, a condition that is achieved in the element neon. Neon, with a positive charge of 10, has 2 electrons in the first shell and 8 electrons in the second shell (see Fig. 4). Thereafter, additional electrons start
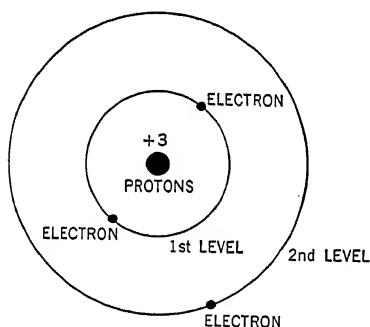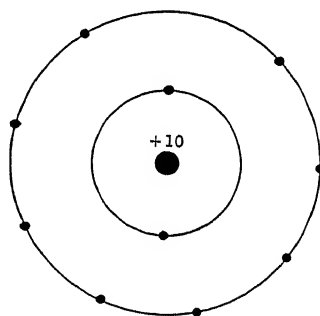

FIG. 3. The atomic structure of lithium.

FIG. 4. Neon, with a positive nuclear charge of 10, has 2 electrons in the first shell and 8 electrons in the second shell.

filling up a third level which can hold 18 electrons and then a fourth level which can hold 32 electrons. Beyond this, there are two additional shells, but these are never entirely filled because there are only 101 elements in all. (Hence, we do not actually know just how many electrons they could hold.)

COMPARISON OF ATOMIC STRUCTURE AND SOLAR SYSTEM

The structural arrangement of an atom, with the central nucleus and the revolving electrons, has often been compared with our own solar system (Fig. 5). In this analogy, the atomic nucleus is equivalent to

the sun and the revolving electrons are each equivalent to the planets. Actually, many differences exist between the two systems, as the reader can appreciate. In the solar system, each planet follows its own path independently of the others; no two planets are equidistant from the sun. In the atom, the electrons revolve at certain specific distances for which we have used the name of shell. It must be recognized, of course, that there is nothing physical about these shells. They merely represent certain energy levels, and each level can carry a certain number of electrons.
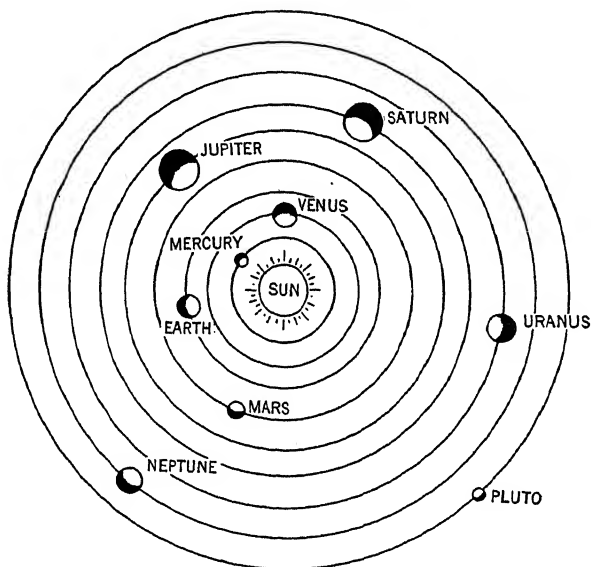

FIG. 5. The solar system. In a limited sense, the central nucleus of an atom may be compared to the sun and the atomic electrons may be identified with the planets.

It is also important to note that even in atoms containing large numbers of revolving electrons, there is still more empty space than there is solid material. The nucleus is rather closely packed, and it contains practically all the mass of the atom. Electrons provide only a negligible portion of the atomic weight, even though their combined electrical charge is equal to that of the far heavier proton.

To emphasize the relatively great distances that separate the nucleus and the first shell of electrons, it has been estimated that if we were to enlarge a hydrogen atom so that the central proton attained the size of a golf ball, we would find each of the electrons to be as large as

tennis balls situated about 20 miles away. Thus, it is readily possible for two atoms to pass through each other's system without coming into physical contact with each other.

COMPOSITION OF NUCLEUS

The composition of the central nucleus has been indicated to consist solely of protons. Actually, this is true only for the simpler elements. As the elements increase in atomic number, it is found that the nucleus may contain electrons as well, with each such electron paired off with an offsetting proton. The net electrical charge of this combination is zero, and hence it does not influence the net positive charge of the nucleus. To achieve this charge, we must have unattached protons. Thus, when we say that a nucleus has a positive charge of 15, for example, we mean that it has 15 "free" protons. Actually, there may be more protons in this nucleus, but all those beyond 15 have their charge neutralized by electrons which are bound to them within the nucleus.

This combination of a proton and a closely bound electron is called a neutron, the name stemming from the fact that the electrical charge is zero. In the lighter elements, those with relatively small numbers of revolving electrons, the number of nuclear neutrons is generally equal to the number of free protons. However, as the atomic number increases, the number of neutrons rises faster than the free protons. These neutrons add as much mass to an atom as a proton and hence are an important factor in the over-all weight of an element. Actually, each neutron adds somewhat more mass than a proton because neutrons possess an electron too.

It may be added that in recent years two additional particles have been discovered in the nucleus: the meson and the neutrino. The meson may have a positive or negative charge, while the neutrino is devoid of charge. The mass of each particle is quite small, scarcely enough to be a significant factor in the over-all atomic weight of the element.

The foregoing discussion has been given in some detail so that the reader will better understand transistor operation. The transistor is a solid-state substance composed essentially of atoms of germanium arranged in a definite geometric pattern. The flow of current through this substance depends upon our ability to dislodge electrons from the outer shell of the various germanium atoms. Hence, it was first necessary to understand how the electrons are distributed around the nucleus of an atom. Now, with this appreciation, we can turn our attention to additional data concerning electron behavior in atoms.

ELECTRON BEHAVIOR IN ATOMS

It was noted in the preceding discussion that the electrons filled the first shell first, then the second shell, then the third shell, etc. In a stable atom, no electrons exist in an outer shell unless those in prior shells are completely filled.* Furthermore, a shell is in its most stable state when it carries a full complement of electrons. For the innermost level, this means 2 electrons; for the next shell, this means 8 electrons; etc. It has been found that elements whose outer ring is not complete are more chemically active than elements whose outer ring is complete. A good illustration of the former is sodium. The atomic number of this element is 11, and its two inner rings or shells are each filled to capacity (i.e., 2 and 8 electrons, respectively). The third ring contains 1 electron and since sodium would be more stable without any electrons in this third ring, we find that sodium is chemically active because it readily loses or gives up this sole electron. As a matter of fact, sodium is so anxious to give up its extra electron that it is never found by itself in nature. A suitable element that combines readily with sodium is fluorine to form sodium fluoride. These two elements react particularly readily with each other because chlorine˙ (atomic number 9) has 7 electrons in its second ring and the addition of 1 electron more completes this ring. Thus, one way of looking at this combination is to consider the sodium atom as giving up its lone third-ring electron to form a stable atom having two completed rings or shells while fluorine receives this extra electron and it, too, forms two complete shells.

Another explanation of this combination is to say that both sodium and fluorine share these additional 8 electrons with each other, permitting each to have completed outer rings. That is, fluorine uses the 1 sodium electron to complete its second shell while sodium uses the 7 fluorine electrons to complete its third shell. The latter view is perhaps the more realistic one, since obviously the sodium and fluorine atoms (in the sodium fluoride salt that is formed) do not leave one another but rather coexist in a crystal structure. This view will also provide a better insight into transistor action, because electron sharing is an integral part of the germanium crystal.

From this "desire" on the part of an atom to attain a state where its

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* This is true for the first three shells; in the fourth and higher shells, there is less tendency to follow this rigorous pattern, probably because, with increasing distance, the influence of the nucleus on the outer electrons decreases rapidly.

outer shells possess a complete complement of electrons, we can also surmise that atoms in which this is naturally true will be extremely stable and "well-satisfied" and will not enter *easily* into chemical combination with other elements. There are six such elements: helium, neon, argon, krypton, xenon, and radon. In helium, the first ring is complete with 2 electrons. In neon, the next heaviest of these atoms, there are 2 electrons in the first shell and 8 in the second shell. Argon, the third inert element, has 18 electrons divided into three shells. The first shell is complete with 2 electrons, the next shell has its full quota of 8, and the third shell has 8 electrons. Since the maximum capacity of the
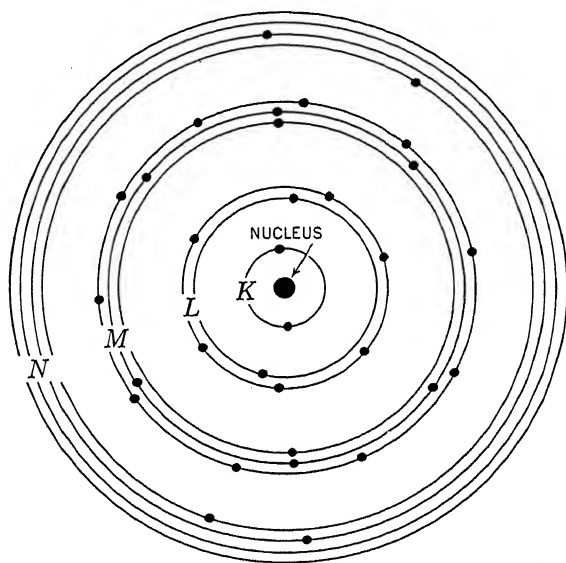

FIG. 6. All energy levels or shells beyond the first (K) are divided into subshells. Each group of shells is designated by a different letter, beginning with K. This is followed by L, M, N, O, P, and Q. The first subshell of any group is given the letter s, the second subshell p, the third subshell of any group having three (or more) is labeled by the letter d, and the fourth subshell is labeled f. No known element possesses more than four subshells as far as we now know. (The arrangement shown above is for the element germanium.)

third shell was previously indicated to be 18, it would appear that in argon this shell is not complete. However, this is not true because it was found that all shells beyond the first one can be divided into subshells (see Fig. 6). For the second main shell we have two subshells, one holding a maximum of 2 electrons and one a total of 6 electrons.

Note that the total previously given for this second shell, 8, still holds. However, the 8 is divided into two subshells of 2 and 6, respectively.

For the third main shell, the maximum number of electrons is 18, divided into three subshells of 2, 6, and 10. In argon, the first two subshells are complete, and this has the same stabilizing effect as though we had completely filled all three subshells. [This behavior also explains why sodium is "satisfied" when it shares its electron with fluorine's 7 electrons in its (sodium's) third shell. What happens here is that the first and second sublevels of the sodium third shell are filled.]

In the inert element krypton, the atomic number is 36, and here all sublevels of the first three main shells are filled with electrons.

The key, then, to the chemical behavior of any element is directly related to the number of electrons contained in its outermost shell and how close this shell comes to being filled. If the shell (or one or more of its sublevels) is filled, the atom needs no additional electrons and therefore it has no tendency to enter into chemical combination with other elements. If the shell is not filled, the atom does seek other electrons and we say it is chemically active.

This chemical activity can also be related to electrical conductivity, because an atom whose outer ring is filled shows no tendency to part with any of its electrons. Since we need free electrons to obtain an electrical current, these inert elements are insulators. On the other hand, atoms which part easily with an electron in order to end up with a complete shell make good conductors. Copper, for example, has an atomic number 29; this means that all subshells of the first three main shells are completely filled (i.e., 2, 8, and 18), leaving 1 electron for the first subshell of the fourth ring. It is fairly easy to take this end electron away from copper, and hence, copper forms an excellent conductor of electrical currents.

Note that if we were to attempt to take away more than 1 electron from copper, we should have to apply a considerably greater amount of energy. This is because the second electron would have to come from a complete ring, and since this is a particularly stable condition, the atom would resist this removal with tenacity. However, if we applied enough energy, electron removal could be accomplished.

ELECTRON REMOVAL

When one or more electrons are removed from an atom, that atom is no longer electrically neutral in charge. If we remove 1 electron, the nucleus has one positive charge more than the outer electrons and the

over-all charge is +1. The atom has now become what is known as an ion and, in the present illustration, a positive ion.

It is also possible for an atom to gain an electron, and when this occurs, the over-all electrical charge becomes −1. The atom in this instance becomes a negative ion. Situations such as this occur when an atom needs one more electron to complete a ring. It then attempts to obtain this additional electron from some other element, particularly one possessing a lone electron in its outermost ring.

Energy is required to remove an electron from an atom. That is, atoms do not part with any of their electrons unless they are forced to do so, and one way to pry an electron loose is to provide it with enough energy to escape from the attractive force of its positive nucleus. Commonly used forms of energy, particularly in electronic devices, are electric fields, heat, light, and bombardment by some other particle. In wires, for example, we force the copper atoms to give up an electron each by applying an emf across the ends of the conductor (Fig. 7a). In a vacuum tube, we heat a cathode until the outer
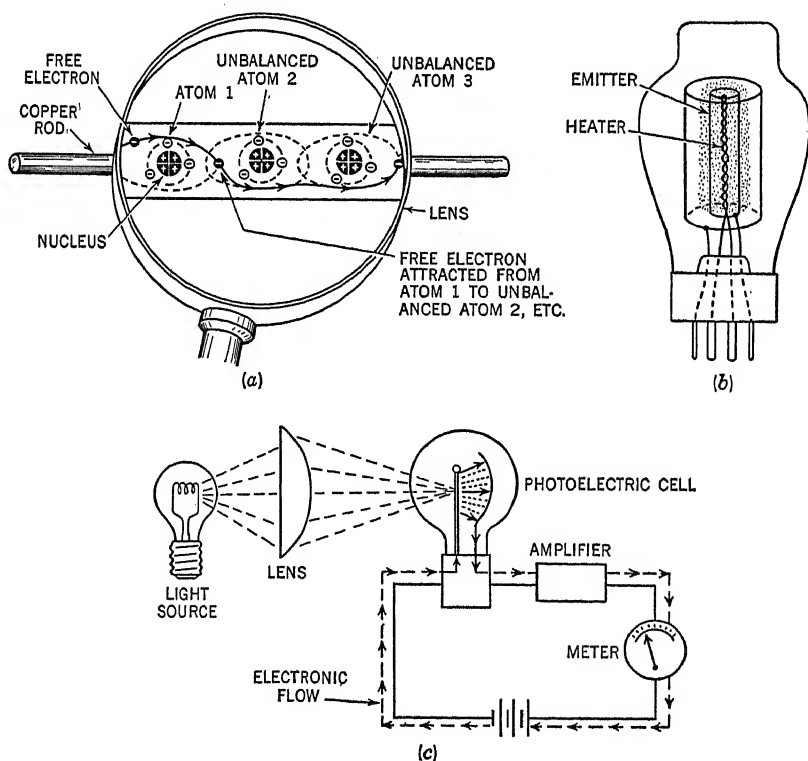

FIG. 7. Several common methods of separating electrons from their atoms.

ring electrons have absorbed enough energy to escape from their respective atoms and leap into the interelectrode space (Fig. 7b). Here they are further attracted by a positive emf on the plate, and thus we get a flow of current through the tube and the outer circuitry of the system. Light, as an activating agent, is employed in photoelectric tubes, where the energy which light rays bring to the atoms of the photoelectric cell enable some of their electrons to escape and again reach a positively charged anode (see Fig. 7c).

Finally, bombardment to produce ions is the basis of operation of gaseous tubes such as the thyratron. Thus, ionization is as important to the electronics industry as it is to the chemical industry. And ionization, no matter where it occurs, is due to a transfer of energy from one substance to another.

THE QUANTUM THEORY

The mechanism by which bound electrons are freed has been the subject of a considerable amount of investigation, and certain facts have been discovered which are important to us in our study of transistors. For example, it has been revealed that when we supply energy to an electron held in an atom, we must supply a definite amount of energy in order for it to have an effect on the electron. The various shells in an atom represent definite energy levels, and in order to move an electron from a lower shell (or subshell) to a higher shell, a certain amount of energy is required. Failure to provide enough energy to the electron will cause it to remain at its present level. This is true even if the energy provided is just barely shy of the required amount.

By the same token, if more than enough energy is provided for the electron to leave its orbit and move to the next higher level, then the excess will be to no avail *unless* enough extra is provided to enable the electron to move to a still higher shell. In other words, energy is required in definite, discrete amounts called quanta, and the electrons can receive these quanta only in whole numbers, such as 1, 2, 3 quanta, etc.

Electrons can lose energy as well as receive it, and when an electron in an atom loses energy, it moves to a level which is closer to the nucleus. This lost energy may appear as heat, as in a conductor when current is passed through it, or as visible light, as in a gaseous tube. In the latter devices, the light emitted by the electrons of the gas molecules produces a visible haze. In fact, one of the ways of recognizing gas in a vacuum tube is by the bluish light it emits. This merely represents electrons returning from some outer shell to an inner shell.

Different elements have different energy levels for their electrons, and consequently, the amount of energy absorbed or released varies as the electrons move from level to level. This accounts for the different-color light emitted by various substances when they are excited. Heating sodium over an open flame produces a characteristic yellow light; neon gas, when activated in electric signs, emits an orange-red glow. The energy required to produce red light is less than the energy needed to produce blue light. This is because the energy in a quanta bundle depends on frequency and red has a lower frequency than blue.

Another fact which is brought out by this theory of quanta explains in more precise terms the differences between electrical insulators and electrical conductors. Previously we indicated that this difference was due to the number of electrons in the outermost shell of an atom that was occupied. This reasoning still holds, but it can now be presented in more specific terms. The mathematics involved in a full presentation is far beyond the level of this text and certainly not required for our particular objectives. However, what this investigation does make clear is useful here. For example, materials which are insulators can be depicted as shown in Fig. 8a. In the lower section of the illustration, the portion labeled as the valence or filled band represents the energy levels, or shells, which are closest to the nucleus and, in a normal atom, contains the correct number of electrons needed to offset the positive charge of the nucleus. In the $n = 1$ shell, 2 electrons would be found; in the $n = 2$ shell, 8 electrons would be found; etc.

Above this valence band is a series of levels that collectively form the forbidden band. For some reason which is still not fully understood, electrons are never found in this band. Electrons may jump back and forth from the bottom valence band to the top conduction band, but they never come to rest in the forbidden band.

The final band of Fig. 8a is the conduction band, and it is the electrons in these energy levels which take part in any movement of electrons through a substance; i.e., it is these electrons that produce electrical currents.

The illustration in Fig. 8a is labeled "Insulator" because of the wide extent of the forbidden band. The wider this band, the greater the amount of energy which must be fed to any electron in the valence band in order to bring it up to the conduction band where it can be employed as a carrier of electricity. Obviously in an insulator, a lot of energy is required to get even a minute amount of current through the substance.

In a semiconductor, the extent of the forbidden band is smaller (Fig. b), which means that less energy need be fed to the electrons in the

valence bands in order to bring them through the forbidden band and into the conduction band. Hence, in semiconductors, more current will flow for a certain applied voltage, although this current will not be so large as we would obtain in a conductor.

The third illustration (Fig. 8c) is for a conductor. Here we see that the valence and conduction bands overlap. It now takes a very small
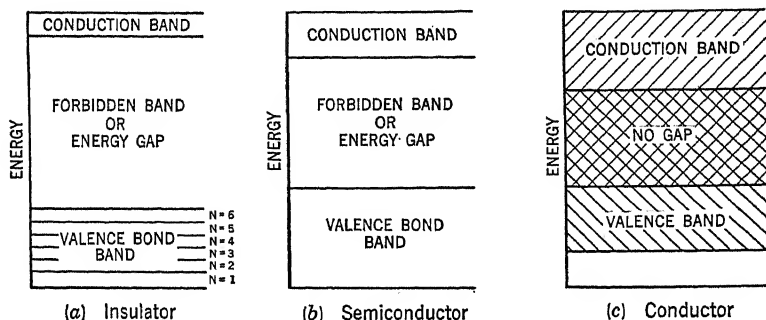

FIG. 8. The difference among insulators, semiconductors, and conductors in terms of their valence-bond bands, forbidden-bond bands, and conduction bands. In illustrations b and c, the various energy levels in each band are omitted. In illustration a, the energy levels are shown only for the valence-bond band.

amount of energy to move electrons into the conduction band, and consequently, electricity is readily passed by conductors. All this, of course, is common knowledge; what is not so universally known is how the various energy levels of an atom cause it to act as an insulator, semiconductor, or conductor. This is where the quantum theory so admirably fills in the gaps, and that is what we have attempted to make clear in this discussion.

The side axis of each of the three illustrations in Fig. 8 is labeled simply as "Energy." It is the generally accepted practice for physicists to use electron volts as a convenient measure of energy. One electron volt is the energy acquired by an electron in falling through a potential difference of 1 volt. If we used this method of measuring energy, then the width of the forbidden band in an insulator is 1 electron volt or more. For a semiconductor such as germanium, the width of this band is 0.7 electron volt. And for conductors, where the forbidden band is absent, we need perhaps 0.05 electron volt to bring an electron into the conduction band.

It should be understood, of course, that the three illustrations of Fig. 8 are each representative of a class of materials and many substances will naturally exist whose characteristics fall somewhere in between

those of insulators and semiconductors on the one hand and semi-conductors and conductors on the other. Germanium, for example, in the highly purified state, is an exceedingly poor conductor of electricity. However, as we add certain controlled amounts of impurities to germanium, we find that its conduction increases materially, indicating that while a substance may be basically an insulator, its properties can be altered. The latter is actually what happens in germanium and silicon transistors and is responsible for the ability of these units to function as amplifiers.

QUESTIONS

1. What advantages do transistors possess that make them especially attractive for communications applications?

2. Differentiate among atoms, molecules, and elements. Name 15 elements that you have personally come in contact with, either singly or in combination.

3. Describe the structure of an atom in general terms. Compare this structure with that of the solar system.

4. How are the electrons arranged within an atom? Consider first a simple element, then a fairly complex element.

5. What differences exist between the nucleus of a simple atom, such as hydrogen, and the nucleus of a complex atom?

6. What causes an element to be chemically active? Stable?

7. Is there any apparent relationship between the chemical activity of an atom and its electrical conductivity? Explain.

8. What happens when an atom gains an additional electron? Loses an electron? What is the altered atom called?

9. What methods may be used to remove electrons from an atom? Describe one or two methods in detail.

10. What is the quantum theory with respect to electron removal?

11. Define the valence band, conduction band, and forbidden band.

12. Explain the difference among conductors, insulators, and semiconductors in terms of energy bands.

CHAPTER 2

POINT-CONTACT AND
JUNCTION TRANSISTORS

Introduction. It was noted, in the preceding chapter, that the chemical activity of an atom is determined primarily by the number of electrons contained in the outermost ring of the element. When this ring is filled, the element is stable and shows little inclination to combine with any other element. The activity increases, however, when the number of electrons is less than the full number needed to complete a ring. Because of the importance of these electrons, they are given the special name of valence electrons. Furthermore, it is common practice in illustrations of atoms to show only the valence electrons (see Fig. 1). The carbon atom, with an atomic number 6, is shown here. The $+6$
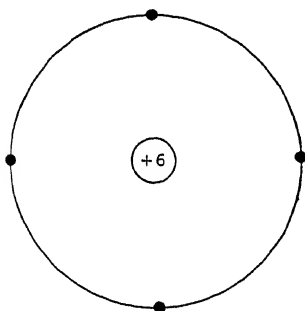

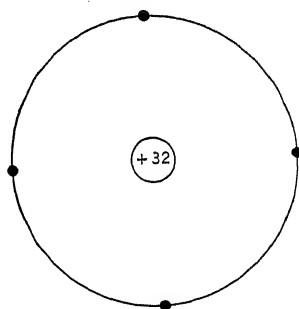FIG. 1. A simplified illustration of the carbon atom. Only the valence electrons are shown.

FIG. 2. The germanium atom, using the simplified method of presentation.

at the center represents the nuclear charge. Since there are 4 valence electrons, we know that these electrons are in the second ring; the 2 electrons not shown would be in the first ring.

Of immediate interest in transistors is germanium, and this element, too, contains 4 electrons in its outmost ring. The atomic number of

germanium is 32, giving us three completed shells of 2, 8, and 18 electrons each and 4 electrons in the fourth shell. The latter electrons are the valence electrons, and they are the ones represented in Fig. 2.

LATTICE STRUCTURE AND CRYSTALS

Germanium in the solid state possesses a crystalline structure in which a group of germanium atoms combine, through their valence electrons, to form a repeated structure having a number of basic cubical lattices such as shown in Fig. 3. Each of the dark "balls" in the illustration represent the germanium atom; the rods between the balls represent the electronic forces binding each atom to its neighbors.

This cubical configuration, known as a diamond structure, is characteristic of the solid state of a number of elements, among them carbon, silicon, and germanium. A large, visible crystal of germanium would be composed of millions upon millions of these basic cubical lattices.

A two-dimensional illustration of the manner in which the germanium atoms are bound to one another is given in Fig. 4. Focusing our atten-
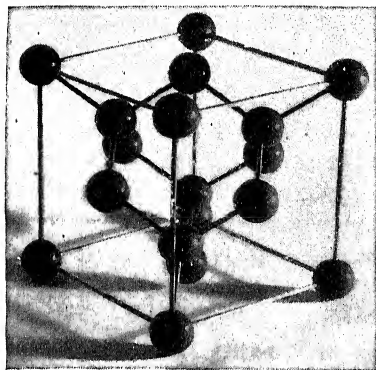

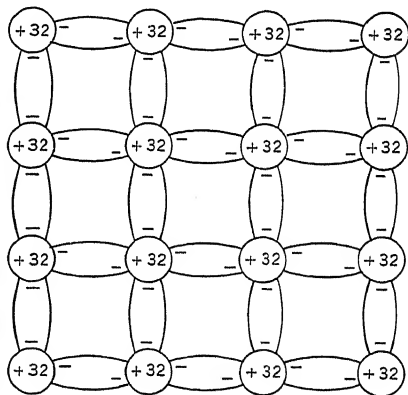FIG. 3. An illustration of the crystal lattice structure of germanium.

FIG. 4. Representation of electron-paired bonds in germanium.

tion on any one of the central atoms, we see that each of its 4 electrons is shared by four other germanium atoms. This gives the central atom a total of 8 electrons in its outermost ring; four of these electrons represent its own electrons, and the other four, electrons which it "borrows" from the surrounding atoms. Since 8 electrons in a ring (actually, here, a subring, since the fourth level can hold up to a maximum of 32 electrons) provide for a stable arrangement, the germanium crystal thus forms a stable compound.

What is true of the central atom is true of all its neighbors, each sharing its four outer electrons with four other germanium atoms. This, too, is shown in Fig. 4 for a limited number of atoms. All the valence electrons are tightly held together. Consequently, pure germanium is not a very good conductor of electricity. A good conductor would require an abundance of free electrons, and as we see, all electrons in a germanium crystal are held fairly tightly because, in combination, they tend to complete the outer subring of the germanium atoms.

That the substance is not a complete insulator, but rather a semiconductor, stems from the fact that thermal agitation, arising from the energy imparted to the electrons by the heat of its surroundings, causes an electron here and there to break away from its bond and wander through the crystal lattice structure in a more or less aimless manner.

ELECTRONS AND HOLES

The bond from which an electron escapes is now left with a deficiency of 1 electron, and hence we should find here a positive charge of 1. This electron deficiency has been given the rather descriptive name of "hole," as though a physical hole had actually been left by the removal of the electron.

We have been conditioned by our previous training to accept the fact that electrons are quite mobile and may be moved readily from point to point. Numerous tests have been performed in which this fact has been demonstrated, and in our own experience with electrical circuits we have never encountered any action which would cause us to think otherwise. Hence, when the statement is made, as it was above, that the freed electron wanders aimlessly through the crystal, every reader will accept it without question.

It is, however, also valid in this case to state that the hole left by the electron will also wander about within the crystal structure, and on this point we would run into a general raising of eyebrows. And yet, it has been conclusively demonstrated that holes do travel through germanium crystals. In fact, the concept of hole travel is basic to an understanding of transistor operation and hence warrants a more detailed description.

When a bound electron departs, the charge deficiency, or hole, that it leaves behind is confined to the valence ring of the atom. If, now, a nearby electron held in a covalent bond acquires enough energy to leave its bond and jump into the waiting hole, then in essence what we have had is a shift in position of the positively charged hole from

its first position to this new position (see Fig. 5). This same action can occur a number of times, with successive changes in hole position, so we can very well state that a hole drifts about in a random manner in exactly the same fashion as the electron which left the hole originally.

The foregoing discussion has dealt with a single electron and a single hole, but in actual crystals there would be many such pairs. And with many negative electrons and positive holes present, a considerable number of recombinations will be taking place all the time. By the same token, the energy (be it heat or light or an electric field) being supplied to the crystal will constantly be breaking other bonds. Eventually, a dynamic equilibrium will be reached in which the number of bonds being broken will equal the number being reformed.

If the energy supplied to the crystal is an electric field developed by the application of an

FIRST HOLE NOW BEING FILLED BY ELECTRON FROM LOWER BOND

HOLE LEFT BY ELECTRON IN MOVING IN DIRECTION OF ARROW

FIG. 5. Method by which holes travel through germanium lattice structure.

emf across the germanium crystal, then the motion of the electrons and the holes will be less random and more directed along lines determined by the voltage. Electrons will move toward the positive terminal of the battery, while the holes will drift toward the negative terminal of the battery. The opposite flows of these two charges do not, as one might suppose, cancel each other. Rather they aid each other. This was demonstrated in an experiment performed in 1889 by the physicist H. A. Rowland. On an ebonite disk he placed negative charges of static electricity, separated by raised portions of the disk. When the disk was rotated at high speed, a magnetic field was produced identical with what would have been expected if a flow of electrons had taken place in a loop of wire in the same direction of rotation.

He then removed the negative charges and replaced them by an equivalent number of positive charges. The disk now was rotated in the opposite direction, and the resulting magnetic field had exactly the same direction as its predecessor. Thus, we obtain the same electrical effect whether we have negative charges (i.e., electrons) moving in
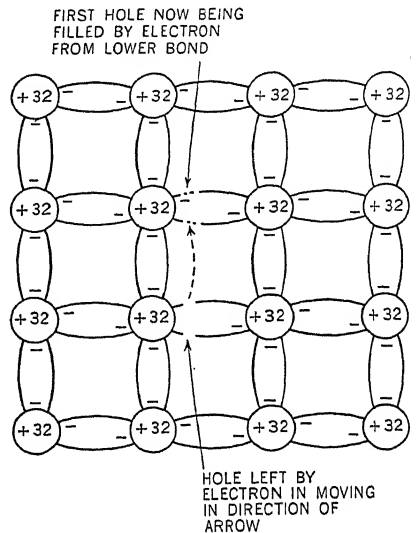
one direction or equivalent positive charges (i.e., holes) traveling in the opposite direction. Ohm's law or any other electrical law we know would yield identical results in either case. This is a significant fact to remember, because all our electrical studies have emphasized electrons and electron flow and the idea of mobile positive charges will come as a surprise. It is particularly important to appreciate both types of current flow, since both occur in transistors.

It is interesting to note that the rate at which electrons and holes diffuse through fairly pure samples of germanium has been determined to be as follows: for electrons, 93 sq cm per sec; for holes 43 sq cm per sec. This is at a temperature of 27°C.* Note how close these two rates are to each other.

N-TYPE GERMANIUM

Externally applied heat and light may be used to produce free electrons and holes in a germanium crystal, but a much more efficient method of achieving the same result is to add exceedingly small amounts of selected impurities, generally to an extent no greater than
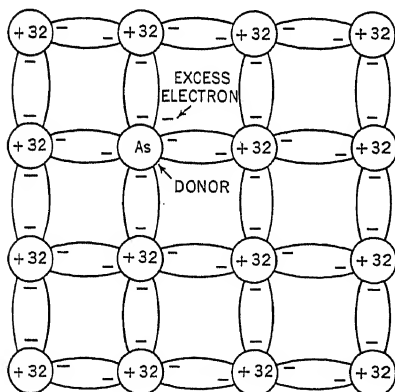

FIG. 6. The effect of an arsenic atom replacing a germanium atom.
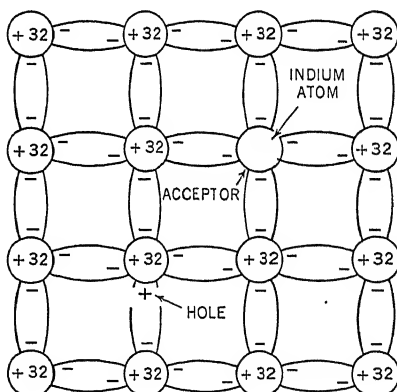
FIG. 7. A hole is produced when a trivalent impurity, such as indium, replaces a germanium atom.

1 part in 10 million. One of the impurities frequently employed is arsenic. This enters the crystalline structure of the germanium and takes the place of single germanium atoms at various points throughout the crystal lattice structure. A diagrammatic representation of this

* These rates are with no applied emf. When a voltage is applied, the rate increases considerably.

condition is shown in Fig. 6. Arsenic has 5 valence electrons, and 4 of these electrons enter into covalent bonds with four surrounding germanium atoms. This is in accordance with the structural arrangement in a germanium atom. The fifth electron is simply held in place by the positive attractive power of the arsenic nucleus. However, since the arsenic atom is sharing its other 4 electrons with four other germanium atoms, in essence it possesses the equivalent of 8 electrons. Since all that the arsenic atom needs for a stable arrangement is 8 electrons, the force with which the extra (i.e., the fifth) electron is held is fairly weak and the bond between this electron and the atom is easily broken. Thus, by the addition of minute quantities of arsenic to the germanium structure we have, in effect, provided the germanium with a source of free electrons. Substances like arsenic or antimony which serve as sources of electrons are called donor impurities. Furthermore, the germanium crystal containing these donor atoms is known as N-type germanium. The N, of course, refers to the fact that the electrical conduction through the crystal is done by electrons, which possess a negative charge.
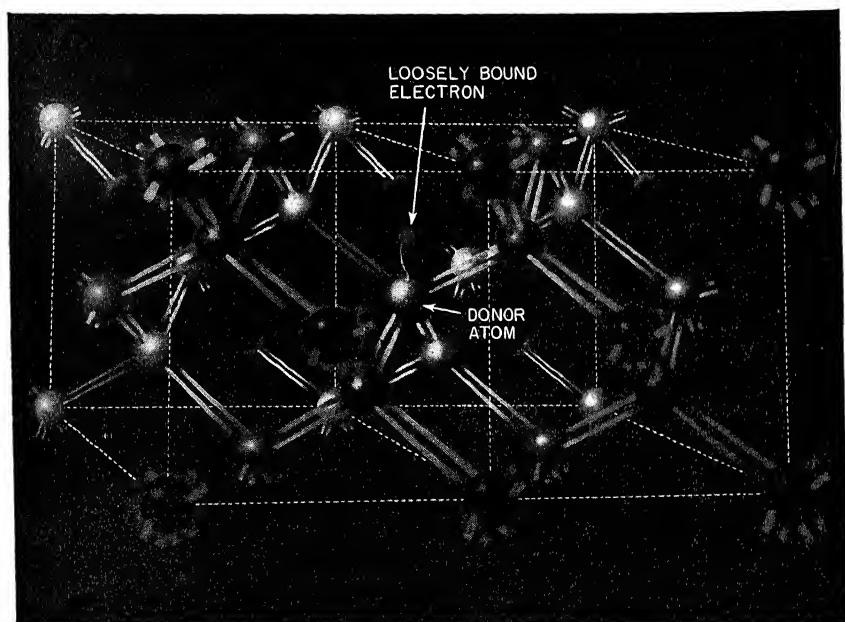
P-TYPE GERMANIUM

It is also possible to add impurities which possess 3 rather than 5 electrons in their outer orbit. Boron, gallium, and indium are examples of such substances. As with the arsenic, each trivalent impurity atom will replace a germanium atom in the lattice structure (see Fig. 7). However, in this case, instead of having an excess of 1 electron, we now find ourselves with a deficiency of 1 electron. In order to complete the four electron-pair bonds, the trivalent atom robs an electron from a nearby germanium bond. The net result of this "robbery" is to leave a hole in the neighboring electron-pair band.

Thus, when the impurity added to the germanium crystal structure has only 3 valence electrons, a series of holes are produced. Under the stress of an applied emf, electrons from other nearby bonds will be attracted to these holes, filling these gaps but creating a similar number of holes in their former bonds. Thus, we have the equivalent of a movement of holes through the crystalline structure, and conduction is said to take place by holes.

Trivalent impurities which create holes are known as acceptor impurities, and the germanium crystals which contain these substances are known as P-type germanium. Thus, by the careful selection of the impurity to be added, we can determine whether the germanium is of the N or P type. Both are employed in transistors, and it is important
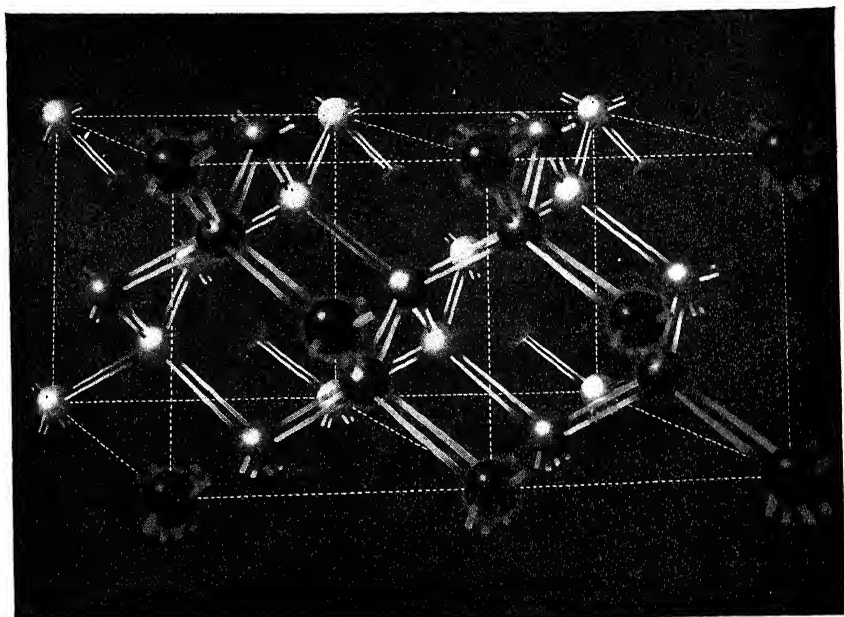
(a)

(b)

A pictorial representation of germanium lattice showing shared electron bonds and the manner in which holes and electrons travel from point to point within the crystal structure. (a) Pure germanium crystal. (b) Donor atom substituted in germanium lattice. Note loosely bound extra electron. (c) N-type conduction. Elec-
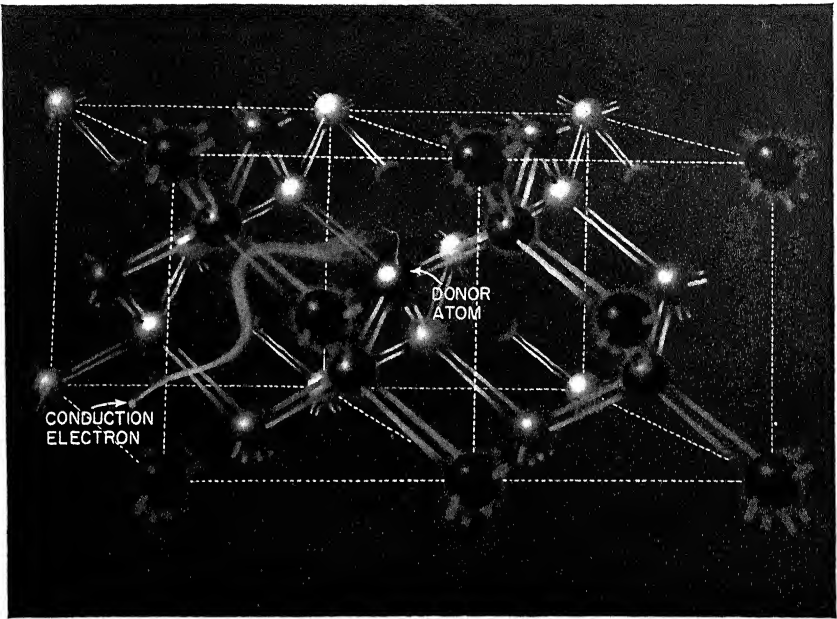
(c)
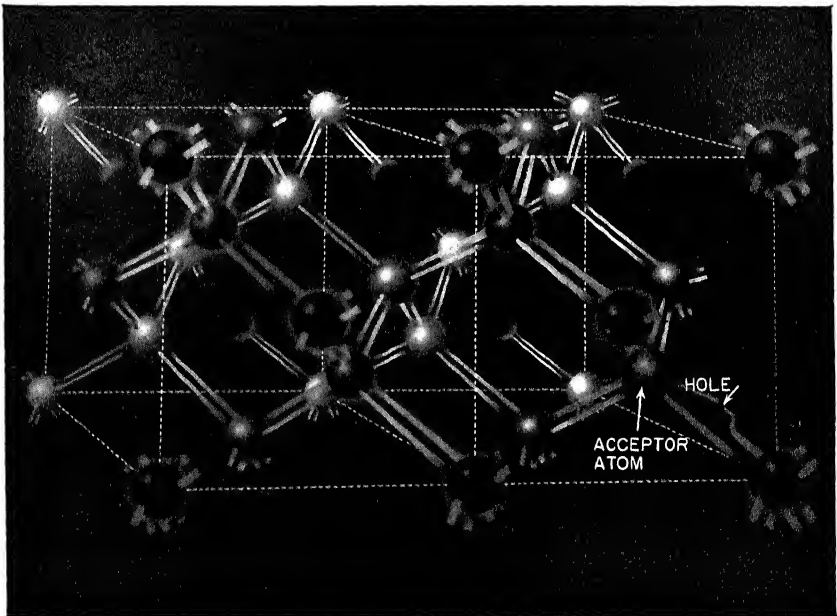
(d)

tron free of donor atom. This may occur because of heat or electrical energy. (d) Acceptor atom substituted in germanium lattice. Note unfilled bond in lower left-hand corner of illustration. (*Continued*)
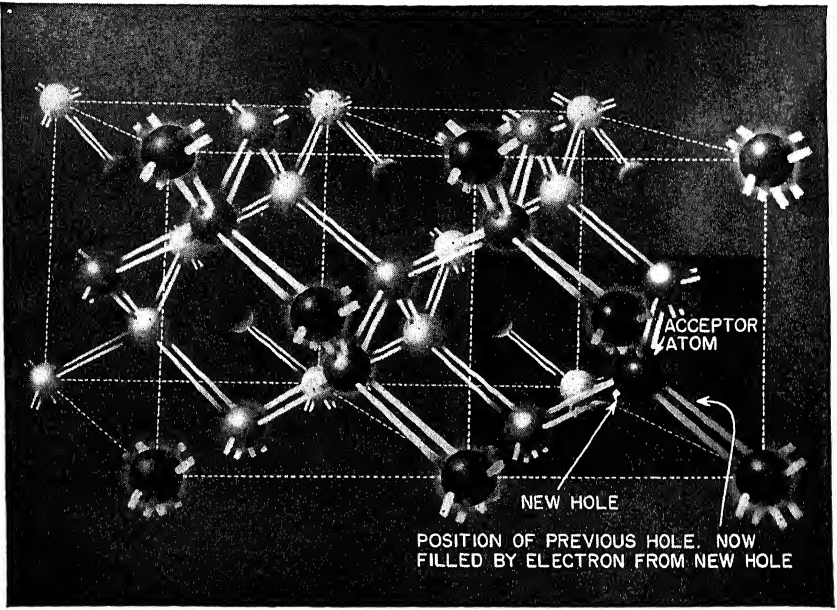
(e)
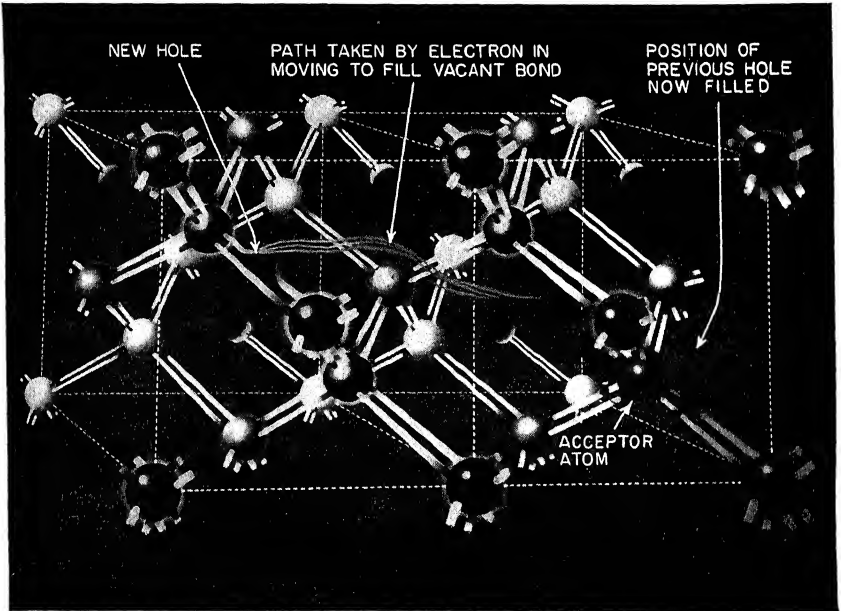
(f)

(e) Filling vacant bond by thermal excitation of electron from nearby bond.
(f) P-type conduction. Hole migrating through lattice by excitation of electron
from bond to bond. (*Courtesy General Electric Company and Electrical Engineering.*)

that the reader understand the differences between them and how electrical conduction occurs through each.

It should be noted that there are a number of holes present in N-type germanium because of the normal breaking of bonds arising from the absorption of heat or light energy.* This is exactly similar to the action in pure germanium. However, the electrons released by the arsenic impurity are, by far, the principal conductors of electricity in N-type germanium. By the same token, free electrons exist in P-type germanium, but again, it is the holes created by the trivalent impurity that account for the major portion of the electrical conduction that takes place here.

The impurities must be added in carefully controlled amounts, otherwise the germanium crystal structure is modified to such an extent that transistor action is not obtained.

The reader may wonder what would happen if both acceptor and donor impurities were added to a slab of germanium. The holes created by the acceptor atoms would be promptly filled by the extra electrons of the donor atoms. If both impurities were present in equal amounts, the excess electrons would just fill the excess holes and the germanium would act as pure germanium containing no impurities (provided the amount of impurities added were minute in quantity). On the other hand, if one impurity were present in greater amount, the electrons or holes it provided would become the principal carriers of electricity.

PN JUNCTIONS

If we take a section of N-type germanium and a similar section of P-type germanium and join the two together, as shown in Fig. 8, we obtain a component which we know as a germanium diode. The N-type
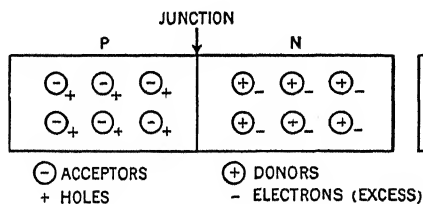

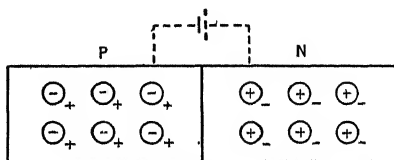Fig. 8. A PN junction forming a familiar germanium diode.

Fig. 9. The battery drawn across the PN junction represents the restraining forces present at the junction.

* The holes in N-type germanium and the electrons in P-type germanium are called minority carriers.

germanium is at the right, and the P-type at the left. The circles at the right with the positive sign represent the donor atoms. They possess a positive sign because their fifth electron has been removed, leaving the atom with a +1 charge. The free electron is indicated by the negative sign.

By the same reasoning, the acceptor atoms in the P-type germanium are represented by a circle with a negative sign, the latter due to the presence of the additional electron which was "robbed" from a neighboring electron-pair bond. The hole left by this electron is represented by a small plus sign.

When these two germanium sections are joined together, one might suppose that the excess electrons on the right would immediately cross the junction and combine with the excess holes on the left. This action, however, does not occur, and the reason ascribed to this is explained as follows. As the electrons in the N-type germanium approach the junction point, they encounter the repelling force of the negatively charged acceptor atoms. It is this force which prevents them from crossing the junction. A few electrons may acquire enough thermal energy to overcome the repelling force and cross the junction, but this is true only of a relatively small number of electrons. The vast majority of electrons are kept on their side of the border.

In an analogous manner, the holes present in the P-type germanium try to cross the junction and are repelled by the positive charge of the donor atoms. Hence, they are forced to remain on their side of the junction also.
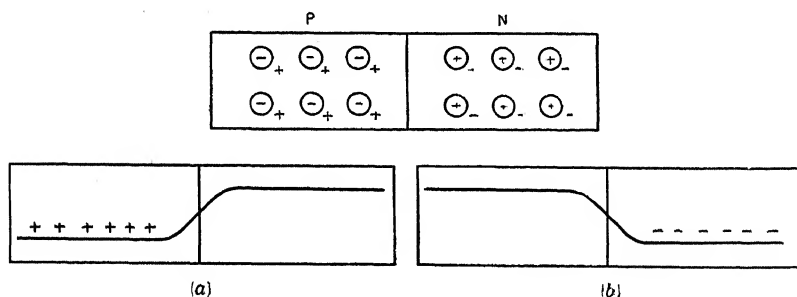

Fig. 10. A second method of indicating the forces present at the PN junction which prevent the combination of the holes at the left with the electrons at the right.

Several pictorial methods have been employed to indicate the restraining forces present at a junction. In one illustration, a small battery is placed across the junction in the manner shown in Fig. 9. The

negative terminal of the battery connects to the P-type germanium, while the positive terminal of the battery attaches to the N-germanium side. Electrons attempting to travel from the N-germanium side to the P side encounter the negative field of the battery and are repelled. By the same token, holes attempting to move from the P side to the N side see the positive battery terminal, and they, too, are repelled.

A second method of representation utilizes what are called potential "hills." The electrons on the N side have to climb a negative potential hill in order to reach the P side (see Fig. 10b). The hill, of course, is the repelling force of the acceptor atoms. On the other side of the junction, the holes have to climb a positive potential hill in order to move to the left (Fig. 10a).

In order to produce a flow of current across the junction, we must neutralize the potential hill that exists here. This can be done by applying an external potential across the ends of the two germanium crystals (see Fig. 11). The negative terminal of the battery connects
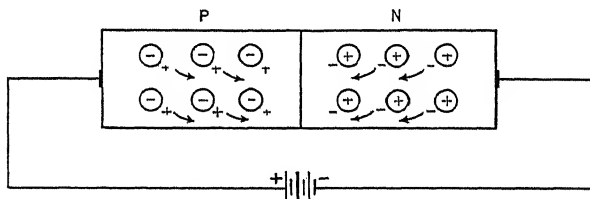
FIG. 11. The effect on the PN junction of application of forward bias.

to the N-type section, and the positive terminal of the battery goes to the P section. The free electrons in the N section are repelled by the negative battery field and move toward the PN junction. At the same time, the positive holes in the P section are forced toward the junction by the repelling force of the positive battery field. If the battery is strong enough, enough energy (i.e., push) will be imparted to these carriers to overcome the potential hill at the junction and enable them to move across to the opposite side. Once the junction crossing is made, a number of electrons and holes will combine. For each hole that combines with an electron from the N-type germanium, an electron from an electron-pair bond in the crystal and near the positive terminal of the battery leaves the crystal and enters the positive terminal of the battery. This creates a new hole which, under the force of the applied emf, moves to the junction. For each electron that combines with a hole, an electron enters the crystal from the negative terminal of the battery. In this way we maintain the continuity of cur-

rent flow. Stoppage at any point immediately breaks the entire circuit, just as it does in any ordinary electric circuit. If this were not so, then electrons would pile up at some point, resulting in a gradually increasing charge or potential at that point. Since this does not occur, we must treat the circuit operation in the manner which has just been indicated.

Note that current flow in the N region is by electrons; in the P region, the current is carried by holes (Fig. 12). As we approach closer to the PN junction, we find both types of carriers. The over-all value of current, however, remains constant and is a function of the applied voltage.
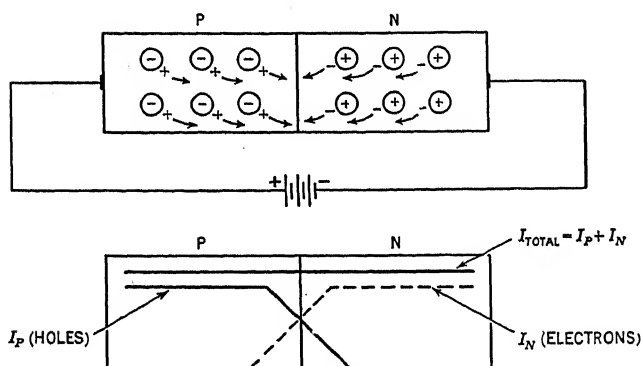
Fig. 12. The current flow in the N region is by electrons; in the P region, the current is carried by holes. In the vicinity of the junction, both types of carriers are present.

As the external voltage is increased, it gradually overcomes the restraining forces present at the junction and the current rises. Once the restraining forces are completely overcome, the current rises sharply as shown in Fig. 13. If the current flow is permitted to reach too high a value, the heat generated will permanently damage the junction and the unit will no longer function in the manner described above.

In the preceding discussion, the diode was biased in its forward, or low-resistance, direction. If, now, we reverse the polarity of the applied voltage, we find that the battery acts in consort with the potential barrier at the junction and practically no current passes at all. The diode is biased in the reverse direction.

The reason for the current decrease is readily understood. With the negative battery terminal connected to the P-germanium section, the excess holes, with their positive charge, are attracted away from the junction (see Fig. 14). At the same time, the positive terminal of the

battery at the N side attracts the excess electrons away from the junction.

The over-all characteristic curve of a germanium diode is shown in Fig. 15. The portion of the curve to the right of the zero line represents the forward current, and the reason for the sharp, upward swing of the curve has already been discussed. The swing upward occurs at relatively low voltages, possibly no more than 4 or 5 volts. To the left of the zero line we have the diode characteristic under reverse bias. We see that a current does flow, although it is usually on the order of microamperes and it remains so until the reverse voltage is brought well above 20 to 30 volts for most diodes.
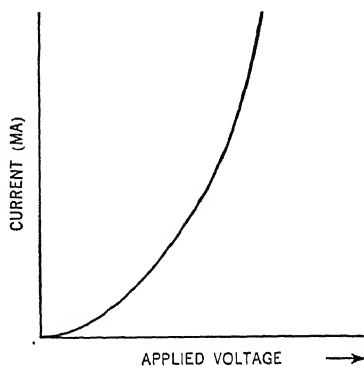
Fig. 13. The behavior of the current flow through a germanium diode as the forward voltage is increased.

The sources of this reverse current are the minority electrons and holes which owe their existence to the light and heat energy striking the crystal. The reverse bias attracts these electrons and holes, and a minute current flows through the circuit. The electrons travel to the positive battery terminal, and as they enter this terminal (or the lead extending from the terminal), an equivalent electron enters the germanium from the negative side of the battery. Similarly, holes move toward
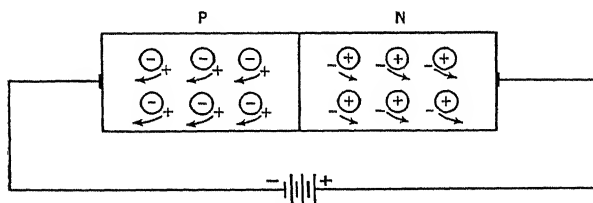
Fig. 14. When the battery connections are reversed, the electrons and holes are drawn away from the PN junction.

the negative terminal, and when they reach this point, they receive an electron with which they combine. For each such combination, one electron leaves a covalent bond in the crystal near the positive terminal of the battery and enters the battery. This creates a new hole which, under the force of the applied emf, moves across the crystal. The situation here is similar to what it was when the battery

voltage was reversed and the majority carriers were involved. Now we are dealing with minority carriers, those electrons and holes that exist on the "wrong" side of the PN junction.

As the value of the applied voltage increases, a point is reached where there is a sharp increase in current. This steep rise is due to the spontaneous breaking of the valency bonds, with considerable number
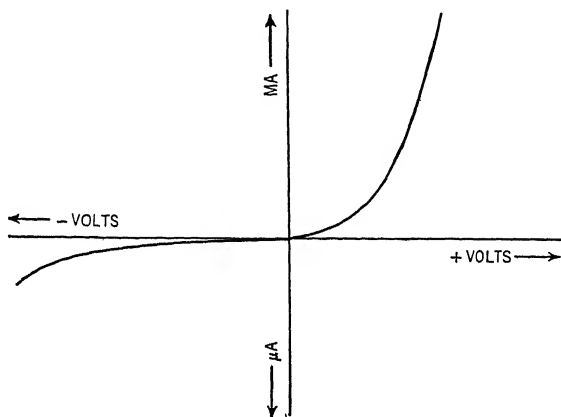
FIG. 15. The over-all static characteristic curve of a germanium diode. The portion of the curve to the left of the vertical line is shown dropping down faster than it should (by comparison with the curve at the right).

of holes and electrons being released. This point represents a breakdown of the crystalline formation, and the voltage which causes this effect is known as the avalanche breakdown voltage. It possesses the same significance in a germanium diode that the maximum inverse voltage rating has in a vacuum tube. In other words, it indicates the reverse voltage level at which excessive reverse current starts flowing through the crystal.

To sum up, then, germanium diodes offer a relatively low resistance when biased in the forward direction and a very high resistance when biased in the reverse direction. This, of course, is common knowledge to the technician. Now, however, the reason for this behavior is indicated.

JUNCTION TRANSISTORS

Thus far we have been considering the operation of germanium and the influence that certain added impurities have on its electrical characteristics. All this has been in the nature of preliminary groundwork for the important task ahead, that of understanding how germanium

transistors operate. We are now ready to take this step, and we shall start with the NPN transistor, which is merely an extension of the PN junction diode just discussed.

An NPN junction transistor is formed by placing a narrow strip of P-type germanium between two relatively wide strips of N-type germanium. This is shown in Fig. 16. Contact to each strip is made by means of a low-resistance plate, with connecting leads from the plates for external circuit attachment.
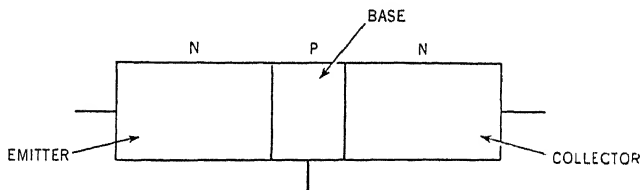
FIG. 16. An NPN transistor and the names of its three sections.

The N-type crystal at the left is called the emitter, the central P-type strip is known as the base, and the end germanium crystal is called the collector. Although these names have no particular significance as yet, they will tie in with the operation of the transistor.

As with the previous PN junction diode, the two end sections contain a number of free electrons, while the central P section possesses an excess of holes. There is no appreciable combination of electrons and holes at the two PN junctions for the same reasons that were indicated for the diode.

Transistor Biasing. To employ this NPN transistor as an amplifier, we would bias the emitter and base sections in the forward, or low-resistance, direction. This is shown in Fig. 17a. At the same time we would bias the base and collector sections in the reverse, or high-resistance, direction (see Fig. 17b). Both bias voltages together are shown in Fig. 17c. Now let us see what happens within the transistor under these conditions.

Since the emitter-base sections are biased in the forward direction, current will flow across their junction. Every time an electron from the emitter section crosses the junction and combines with a hole of the base section, an electron leaves the negative terminal of the battery and enters the emitter crystal. Since the battery cannot continue to supply electrons from the negative terminal without receiving an equivalent number at the positive terminal, then for each electron leaving the negative terminal, the positive side receives an electron

from the base section. This loss of electrons in the base creates holes which then travel to the junction for eventual combination with an electron from the emitter.

(a) Emitter-base biasing   (b) Collector-base biasing

(c) Total biasing
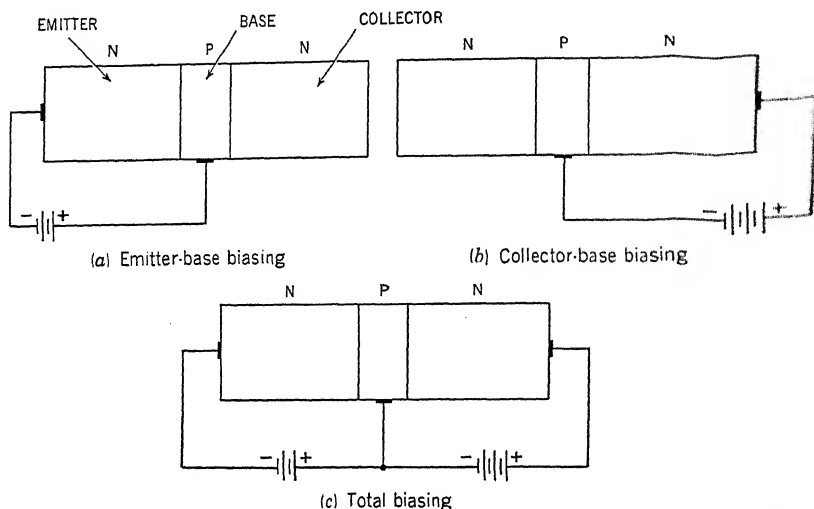
FIG. 17. The proper method of biasing an NPN transistor for use as an amplifier.

Thus far, of course, we are on familiar ground, ground which was previously explored. The main carriers of electricity in P-type germanium are holes. And this is precisely the situation pictured above.

If the center base section were made quite thick, then practically the entire current flow would occur in the manner just described and be confined entirely between emitter and base. There would be little current between base and collector because of the reverse biasing existing here.

However, the base strip is made exceedingly thin, and because of this, transistor amplifying action is achieved. For with the base thin, electrons leaving the emitter pass right through the base section and into the collector region, where they see a positive attractive force that impels them on. Thus, they travel through the collector section and around the external circuit back to the emitter again, completing their path of travel.

At this point the reader may wonder why the emitter current flows through the collector when it was specifically stated that the collector was biased in the reverse, or high-resistance, direction. If we disregard the base for a moment and simply consider the path from the emitter to the collector internally and from the collector to the emitter ex-

ternally, we see that the two bias batteries are connected series aiding. Thus, any emitter electrons that can pass through the base region without combining with the holes present here will find the attracting force of the collector battery urging them on through the collector section. The reverse biasing between collector and base does not affect the emitter electrons that pass through the base and reach the collector.

With the base strip made very thin, the number of combinations between emitter electrons and base holes will be quite small, probably no more than 5 per cent of the total number of electrons leaving the emitter. The remaining 95 per cent of the electrons will reach the collector strip and travel through it. Thus, while the number of electrons leaving the emitter is a function solely of the emitter-base voltage, the element which receives most of this current is the collector. The analogy here to vacuum-tube behavior is very marked. In a tube, the number of electrons leaving the cathode (i.e., the emitter) is governed by the grid-to-cathode voltage. However, it is the plate (i.e., collector) which receives practically all these electrons. In a tube, the amount of current flowing is regulated by varying the grid-to-cathode voltage. In a transistor, the emitter-collector current is varied by changing the emitter-base voltage.

Note, too, that because the base current is very small, a change in emitter bias will have a far greater effect on emitter-collector current than it will on base current. This also is desirable, since it is the current flowing through the collector that reaches the output circuit. (By the same token, it is the current flowing through the plate circuit in a tube that is important.)

Transistor Gain. We achieve a voltage gain in the transistor by virtue of the fact that the emitter-to-base resistance is low (because of the forward biasing between these two elements) whereas the collector-to-base resistance is high (because these elements are reverse biased). A typical value for the emitter-to-base resistance is about 500 ohms, and a typical value for the collector-to-base resistance is about 500,000 ohms. The current that reaches the collector is 95 per cent of the current leaving the emitter. If, now, we multiply the current gain (0.95) by the resistance gain 500,000/500, we shall obtain the voltage gain of the collector circuit over the emitter circuit. Numerically, this is

$$\text{Voltage gain} = \text{current gain} \times \text{resistance gain} = 0.95 \times \frac{500,000}{500} = 950$$

Thus we see that while the current gain here is actually a loss, this is more than made up by the extent to which the collector resistance

exceeds the emitter resistance. Furthermore, this overwhelming dif-
ferential in resistance will also provide a power gain. This means that
with a small amount of power in the input, or emitter-to-base, circuit,
we can control a much larger amount of power in the output, or
collector-to-base, circuit. Both of these characteristics are important;
without them the transistor would have only limited application in
electronics.

The voltage gain indicated above is that which would be obtained
if the transistor operated into a very-high-impedance circuit. Actually,
one of the problems which is encountered in cascaded transistor
amplifiers is that of matching the relatively high output impedance of
a prior stage with the low input impedance of the following stage. This
point will be discussed in greater detail in Chap. 4.

Potential Hills. Because a complete understanding of what happens
within the transistor is so vital to future circuit application, still an-
other approach, based on potential hills, is deemed desirable. This
method (Fig. 18)* reveals the effects of emitter, base, and collector
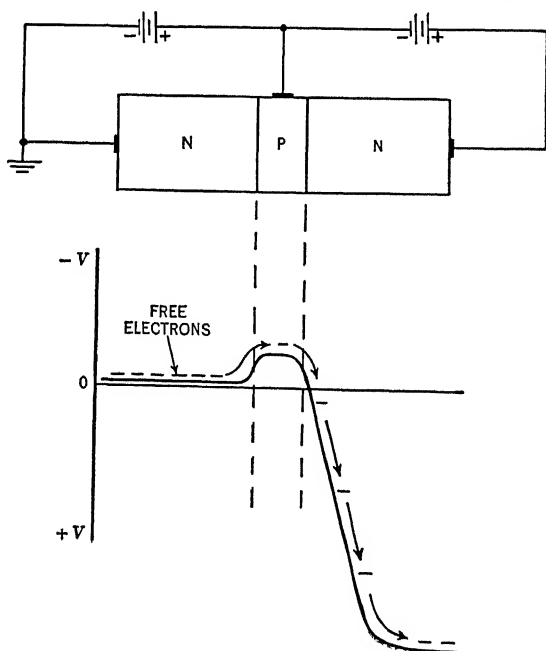
Fig. 18. The potential hill diagram for an NPN junction transistor.

* After H. K. Milward, Introduction to Transistor Electronics, *Wireless World*,
March, 1955.

voltages and presents a simplified visual picture of junction-transistor operation. (We continue to repeat the word junction because we shall presently consider another type of transistor.)

When the emitter is biased in the forward direction and the collector in the reverse direction, electrons leaving the N-type emitter will see a small potential hill in front of them (at the NP junction). However, because of the energy supplied by the applied emf, the electrons will be able to surmount this hill. Once atop the hill, the "ground" levels off and the electrons move through the P layer of the base quite readily. When they reach the junction between the base and the N-type collector, the electrons come under the influence of the positive battery potential and they surge forward strongly. In the voltage diagram, this attraction is represented as a downward slope which electrons (like human beings) find simple to traverse.

If the forward bias on the emitter is reduced, we are, in effect, raising the height of the base potential hill. Electrons leaving the emitter will find the higher hill more difficult to climb, and only those electrons possessing the greatest amount of energy will be able to reach its summit and, from there, move to the collector ahead. Current will consequently be reduced.
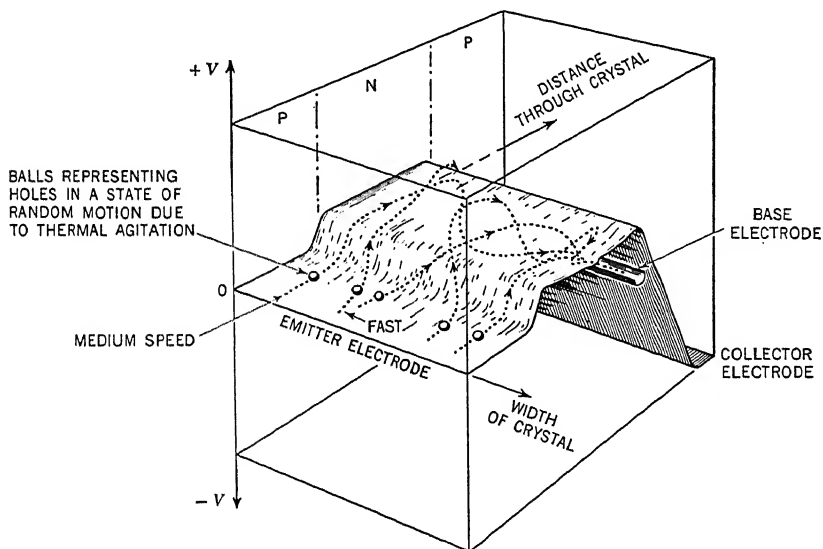
FIG. 19. A three-dimensional representation of the potential levels in a PNP germanium transistor. Suitable bias voltages are assumed applied to the various electrodes. In this illustration, the base is made wider than normal to demonstrate its effect. (Courtesy Wireless World.)

By the same token, increasing the forward bias on the emitter will reduce the height of the hill, enabling more emitter electrons to enter the base region. Thus the biasing voltages used in a transistor have a very important effect on its operation. Another significant controlling factor is the width of the base. This is demonstrated by the next two illustrations.

Two three-dimensional representations of this potential diagram are given in Figs. 19 and 20. The difference between the two drawings lies
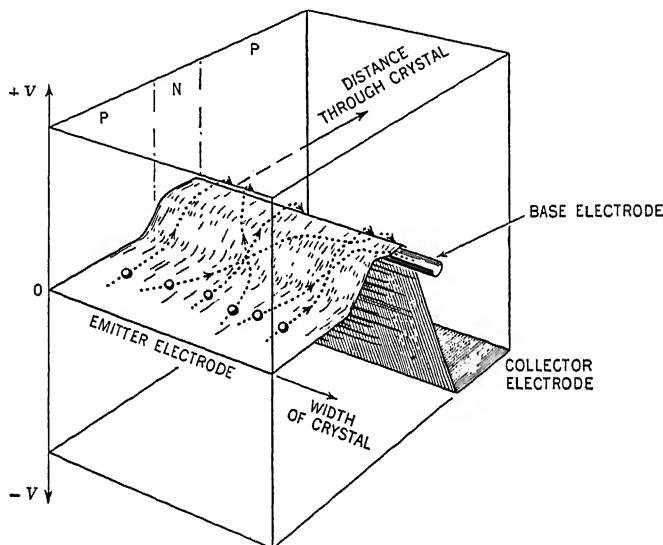
Fɪɢ. 20. The same illustration as Fig. 19 except that the base layer is narrow. (*Courtesy Wireless World.*)

in the width of the base section. If the base section is wide, the tendency for emitter electrons (represented here by balls) to end up at the base electrode (due to combination with holes) is much greater than it is when the base section is narrow. In a physical model of these illustrations, the potential surfaces through the transistor are formed by a rubber membrane supported at several points. The holes in the base section are represented by a slight dip, or valley, at the center of the base membrane. The wider the base section, the more difficult it is for the balls to roll through the base "valley" and over the edge of the precipice into the collector region without being trapped by the base dip.

On the other hand, if the base region is made quite narrow, any

balls having enough energy to surmount the initial rise of the base hill would possess enough energy to reach the far edge of the base and fall down into the collector.

Thus, the width of the base section has a very direct bearing on transistor gain, both voltage and power. For if the percentage of current reaching the collector decreases to very small values, it will reduce the voltage gain in the same proportion. Power, being proportional to the square of the current, will be adversely affected to an even greater extent.

From the foregoing discussion we can formulate two rules concerning this and *all* transistors.

1. The emitter is biased in the forward, or low-resistance, direction.*

2. The collector is biased in the reverse, or high-resistance, direction.

That these rules are always true can be seen if we consider their alternatives. If the emitter is biased in the reverse direction, it will not permit any electrons to reach the base region. And a reverse-biased emitter, with a reverse-biased collector, will produce a transistor in which current never passes.

If the emitter and collector are both forward-biased, then the general tendency will be for the emitter electrons to flow between emitter and base and for the collector electrons to flow between collector and base. In essence we shall have two junction diodes possessing a common base. If the collector forward voltage is larger than the emitter voltage, some of the collector electrons will flow back to the collector via the emitter. But in any event, the desired amplification will not be obtained, and the purpose of the transistor will be defeated.

At this point, a note of caution regarding the application of reverse voltage to transistors. As we shall see later, the emitter bias voltage is quite small, on the order of 1 volt or less. The collector reverse voltage is generally much higher. If we should mistakenly connect the collector battery in the forward direction, the excessive current flowing through this section will develop enough heat to destroy the junctions and render the transistor worthless. Hence, always be certain the collector voltage polarity is correct *before* connections are made.

It is interesting to note that a transistor possesses a bidirectional

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* There are occasions, as with vacuum tubes, when it is desirable to bias the transistor to cutoff. In the case of a vacuum tube, this is done by increasing the negative bias on the grid with respect to the cathode. For a transistor, cutoff is achieved by bringing the emitter-to-base bias to zero or even inserting a small amount of reverse biasing voltage. In the majority of applications, however, the statement indicated above is true.

facility that is impossible to achieve in vacuum tubes. That is, we can forward bias the collector with a low voltage, reverse bias the emitter, and then feed the signal in at the collector. The current gain under these conditions will be somewhat less than it is when the unit is employed normally. As a matter of fact, in Chap. 7, a television phase detector is described in which the emitter and collector sections are structurally identical and each takes turns sending current through the transistor.

Transistor Amplifier. We are now ready to connect this NPN transistor into an actual amplifier circuit with the signal input at one end and the load resistor at the other (see Fig. 21). The incoming signal is applied
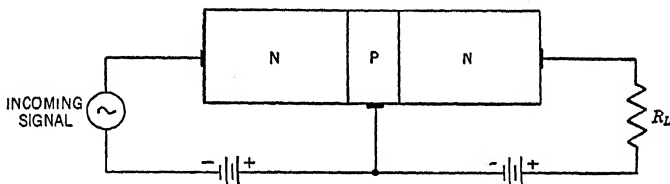
FIG. 21. The NPN transistor connected as an amplifier.

in series with the emitter-to-base bias, and the load resistor is inserted in series with the collector battery. When the signal voltage is zero, the number of electrons leaving the emitter and entering the base region is determined solely by the forward bias on the emitter. This situation can be represented by the potential distribution diagram shown in Fig. 22a. When the signal goes negative, it adds to the forward bias, further reducing the height of the base hill and causing more electrons to flow through the transistor. This is shown in Fig. 22b. During the next half cycle, the signal goes positive, reducing the forward bias of the emitter and thereby reducing the number of electrons leaving the emitter and entering the base and, subsequently, the collector regions. This is shown in Fig. 22c, where the height of the base hill has been increased.

At the other end of the transistor, these current fluctuations produce corresponding voltage variations across R_L, the load resistor. When the input signal is negative and the current increases, the top end of R_L becomes more negative. By the same reasoning, when the signal goes positive, current decreases and the top end of R_L becomes relatively more positive.

Thus, through this transistor, amplification is achieved without the normal 180° phase shift we are accustomed to in vacuum tubes. This
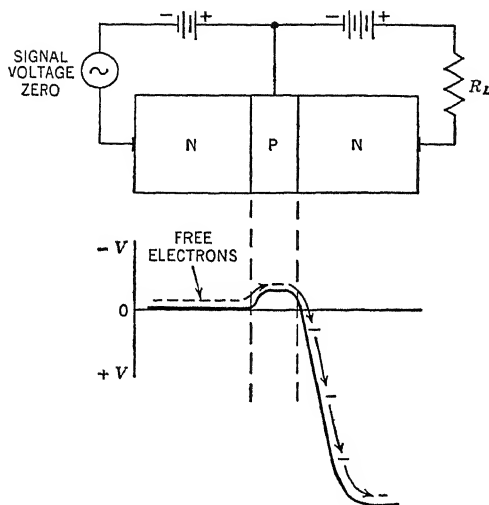
(a) Signal voltage zero
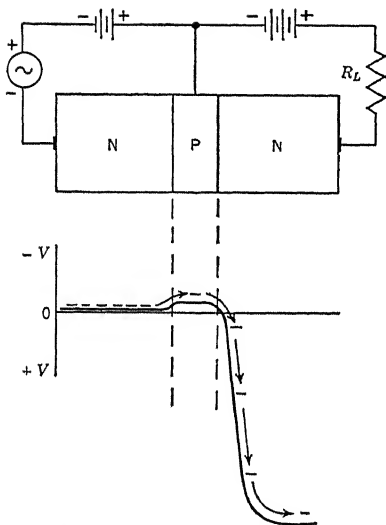
(b) Signal voltage aids emitter-base bias
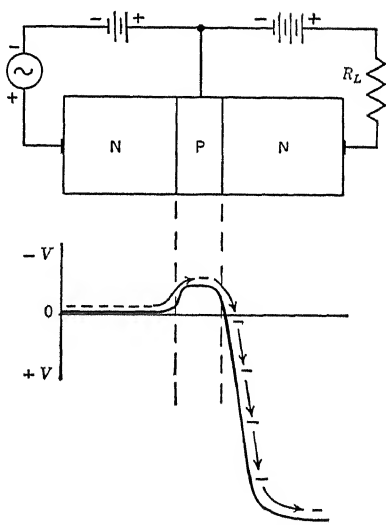
(c) Signal voltage opposes emitter-base bias

Fig. 22. Transistor-amplifier operation demonstrated by potential hills.

is not always true of transistors, and in our subsequent study we shall come across instances when signal phase reversal does occur.

Another point to note here is that with this transistor, an increase in signal polarity (i.e., positive) causes the transistor current to decrease. This is in direct contrast to normal vacuum-tube amplifiers when the

signal is applied to the grid. However, we also know that when the signal is applied to the cathode of a vacuum tube, a positive increase is equivalent to a more negative grid and the plate current decreases.

All this is mentioned in an attempt to illustrate that although transistors and the more familiar vacuum tubes contain many points in common, they also differ in many respects, and it is suggested that the reader learn to think of each in terms of itself. We shall have occasion to make additional comparisons between these two devices. This, of course, is natural, since transistors do the same basic job as vacuum tubes. However, transistors represent an entirely different approach to amplification, with many new features and characteristics. To attempt at each point to find an equivalent property in vacuum tubes for each characteristic in transistors will, in the long run, lead only to confused thinking. Learn to regard transistors in terms of their own operation and vacuum tubes in terms of theirs.

PNP TRANSISTORS

In the formation of the initial transistor from a PN junction, we added a second N section to evolve an NPN transistor. We can approach the same problem by adding another P section to produce a PNP transistor (see Fig. 23). The emitter and collector sections are
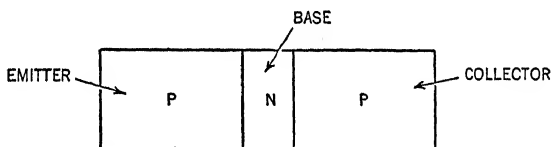
FIG. 23. A PNP transistor.

formed now of P-type germanium, while the base section consists of N-type germanium. Since this is actually the reverse—as far as material structure is concerned—of the NPN transistor, we should expect differences in the mode of operation and in the polarity of the voltages applied to the emitter and collector. However, in spite of these differences, the emitter is still biased in the forward direction and the collector is biased in the reverse direction.

A typical bias setup with a PNP transistor is shown in Fig. 24. The positive side of the battery connects to the emitter, while the negative terminal of the battery goes to the base. The collector battery is attached in the reverse manner, with the negative terminal connecting

to the collector plate and the positive terminal going to the base plate.

Holes are the current carriers in the emitter and collector sections; in the N-type base section, electrons are the principal carriers. With the emitter-bias battery connected as shown, the positive field of the battery repels the positive holes toward the base junction. At the same time, the negative battery terminal at the base drives the base electrons toward the same junction. When a hole and an electron combine at the junction, another electron from the emitter section enters the positive battery terminal. This creates a hole, which then starts traveling toward PN junction. At the same instant, too, that the first hole and electron combine at the junction, another electron leaves the negative battery terminal and enters the base. In this way, current flows through the base-emitter circuit.
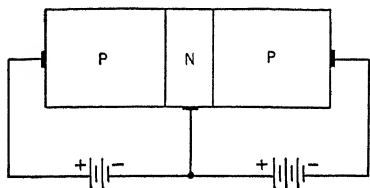
Fig. 24. Method of biasing PNP transistors.
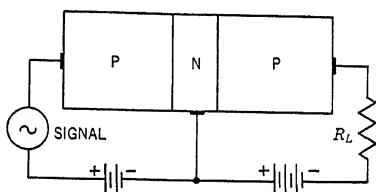
Fig. 25. A PNP transistor amplifier.

In the PNP transistor, the holes are carriers in the emitter section, and when they cross the junction into the base region, a number of them combine with the base electrons. However, well over 90 per cent of the holes do not combine with base electrons; rather, they pass through the base region and continue on to the collector. Here they meet a negative attractive force and move toward the collector terminal. When the terminal is reached, an electron from the battery combines with a hole and effectively neutralizes it. At the same instant, an electron leaves the emitter region and starts on its way around the outer circuit to the collector battery.

Note, then, that although holes are the current carriers in P-type germanium, current conduction through the connecting wires of the external circuit is carried on entirely by electrons. This fits in with the current conduction that we are familiar with.

The incoming signal and the load resistor occupy the same positions in a PNP transistor amplifier that they do in an NPN transistor amplifier (see Fig. 25). Only the polarity of the biasing voltage is reversed.

POINT-CONTACT TRANSISTORS

The discussion thus far has been concerned solely with junction transistors. These were considered first because their internal operation is easier to explain, particularly with respect to the way holes serve as carriers of electricity. However, from the standpoint of discovery and initial development, the point-contact transistor came first. We shall now consider its operation. As with the junction transistor, it is best to start with a point-contact diode, such as we have had available for several years.

Point-contact Diodes. A point junction diode is shown in Fig. 26. One section consists of a small square rectangular slab of germanium to which a controlled amount of impurity has been added. Generally, a
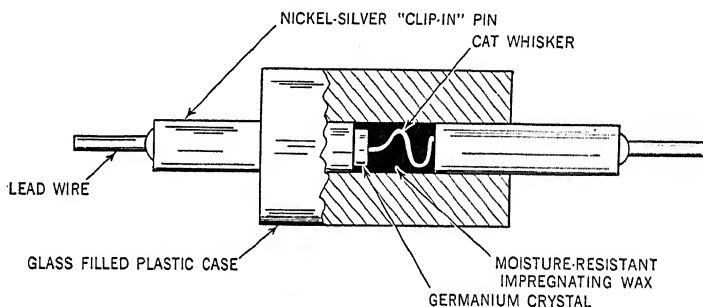
FIG. 26. Cross-sectional view of internal structure of a germanium diode. (*Courtesy* CBS-Hytron.)

pentavalent impurity is added, giving us N-type germanium. The other half of the diode consists of a fine phosphor-bronze or beryllium-copper "cat whisker" wire which presses against the center of the germanium slab. The opposite end of this wire represents one terminal of the diode, while a metal plate deposited on the far side of the germanium crystal serves as the second terminal.

An important step in the fabrication of this diode is the passage of a relatively large current from the "cat whisker" wire to the germanium slab. The purpose of this "forming" current is to produce a small area of P-type germanium in the region surrounding the point of contact of the phosphor-bronze tip. The germanium diode now consists of P- and N-type germanium (Fig. 27), and the explanation of its operation follows exactly along the lines previously indicated for a PN junction diode. Maximum current will flow when the base plate is made nega-

tive with respect to the "cat whisker" wire, and minimum current will flow when these voltages are reversed. The principal current carriers in the N section are electrons, while the principal carriers in the P section are holes. The boundary between the two can be considered as a PN junction, even though the contour of this junction differs considerably from the junctions previously discussed.

Point-contact-transistor Operation. To form a point-contact transistor, two phosphor-bronze wires are mounted side by side as shown in Fig. 28. Each wire has a diameter of 0.5 mil, and their separation is 2 mils. The germanium wafer on which the wires are placed is

FIG. 27. A point-contact germanium diode showing the approximate distribution of the N- and P-type germanium.

approximately 20 mils thick and 50 mils square. One wire forms the emitter of the transistor; the other wire, the collector. A third electrode, the base, is a large-area metal plate deposited on the underside of the germanium wafer. The final preparatory step, and one which is extremely important, is that known as electrical forming. In this process, relatively large surges of current are passed through the wires to the base. As in the preceding diode, this current serves to form small areas or islands of P-type germanium under each wire electrode. The area of each P section is extremely small, possibly no more than a few atomic layers thick. The vagueness of the extent and of even the exact composition of these sections stems from the incompleteness of present knowledge. Transistors, it must be remembered, are only a few years old, and

FIG. 28. (a) A point-contact transistor. The emitter and collector wires are each held tightly against the germanium block. (b) The physical construction of a point-contact transistor.

much investigation into transistor action and its parent field, solid-state physics, remains to be done. It is not inconceivable that some of the theories we are employing here to explain transistor action will, in the light of later developments, require modification or even complete revision. However, enough is known to enable us to form a fairly satisfactory picture of why transistors act as they do.

To understand how a point-contact transistor functions, let us connect the unit into the circuit shown in Fig. 29. The collector is biased
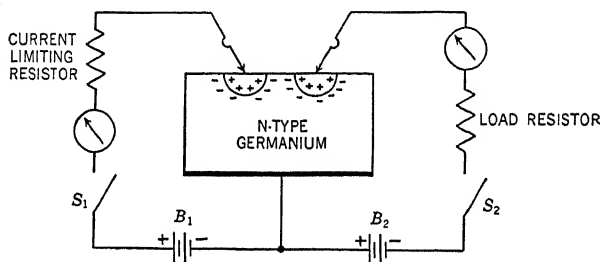
FIG. 29. A point-contact transistor with its bias voltages. These voltages follow the same rules of application as those indicated for junction transistors.

in the reverse, or high-resistance, direction. In this case, since the collector wire is assumed to be the connecting terminal for a P layer, it would receive the negative terminal of the battery. The base, then, would be connected to the positive battery terminal. The emitter is biased in the forward direction; therefore, it connects to the positive terminal of the battery.

Now let us place current meters, switches, and resistors in each of the emitter and collector branches. The resistor in the emitter branch is more in the nature of a limiting resistor, since this portion of the transistor is biased in the forward direction. The resistor in the collector circuit is a load resistor across which the output signal will be developed.

As a start, let us open switch S_1 and close switch S_2. Since the collector is biased in the reverse direction, very little current should flow under these conditions. Actually, with about 25 volts for battery B_2, a current of a few microamperes will be found to flow. This current, like the reverse current in a diode, stems from the presence of free electrons in P-germanium sections and holes in N germanium. These are the minority carriers, and they obtain their energy principally from thermal absorption, although impinging light photons may also be a factor. (The same behavior is displayed by the junction transistor.) If we continue to raise the value of the reverse voltage, we shall eventu-

ally reach a point where the stress of the applied electric field will be great enough to disrupt many of the bonds holding shared electrons in place and a large current will ensue. This occurs at the avalanche breakdown voltage. In the present discussion we are far from this level, and only the slight current mentioned above will be measured.

If, now, we let the collector circuit remain as it is and close switch S_1, two things will happen. First, current will flow in the emitter circuit. Second, the current in the collector circuit will rise. Furthermore, if an input signal is placed in series with the emitter bias, then as the total voltage increases (i.e., becomes more positive), the current in the collector circuit will increase also. On the negative half cycle of the signal, when its voltage is acting in opposition to the bias battery and reducing the over-all positive voltage applied to the emitter, it will be found that the collector current will decrease too. In other words, variations in the input circuit will produce corresponding variations in the output circuit.

It is apparent from this behavior that the emitter circuit influences the collector circuit in point-contact transistors just as it does in junction transistors. Since the area around the emitter "cat whiskers" is P-type germanium and the base is N-type germanium, we can fall back on what we have already learned about junction transistors to attempt an explanation. With the emitter-to-base circuit biased in the forward direction, the holes in the emitter section move toward the base junction (the semicircular boundary of the P area). At the same time, the electrons in the base move toward the emitter junction. At the junction, a small number of the holes combine with base electrons. For every electron that the base loses in this manner, one electron leaves battery B_1 and moves into the base section. In the same way, every hole that the emitter loses by combination forces one electron to leave the emitter and enter the emitter wire on its way to the positive battery terminal. This loss of an electron produces a hole, which then starts migrating toward the base junction.

The majority of the holes which leave the emitter drift toward the collector, attracted by the negative collector voltage. On their way there, some of the holes combine with the free electrons present in the base. Those holes arriving at the collector combine with electrons which the negative terminal of the collector-bias battery provides. For every such combination an electron leaves the emitter section and enters the emitter wire. Electron travel is from emitter through both bias batteries to collector, with the base being completely bypassed. (The reader will note that a similar current exists in junction transistors.)

Now, if the foregoing represented the entire action in a point-contact transistor, then the current flowing in the emitter circuit would be larger than the current flowing in the collector circuit. The difference would be that portion of the emitter current diverted to the base.

Actually, it is found that a change of 1 ma in the emitter circuit of a point-contact transistor produces a 2- to 3-ma change in the collector circuit. Here, obviously, is a significant departure from the effects observed in junction transistors, and the natural question to ask is: "Where does this additional current come from?"

It is believed that the additional current is due to the fact that the emitter holes, in traveling to the collector, form a positive space charge which attracts electrons from other sections of the germanium crystal and causes them to add to the collector current. These additional electrons (which are separate from the electrons that combine with the holes from the emitter) are confined solely to the collector circuit and travel in the path from the negative terminal of the battery through the collector and base sections of the germanium crystal and out through the base lead back to the battery again. In effect, what the holes do is reduce the internal resistance of the collector circuit, permitting a greater current to flow for the same applied voltage. Partial proof of this is the fact that whereas the internal resistance of the collector circuit in junction transistors is on the order of 500,000 ohms or more, in the point-contact resistor, it is typically about 20,000 ohms.

The foregoing behavior in point-contact transistors explains why the two "cat whisker" wires must be positioned close to each other. The greater their spacing, the less likelihood there is of emitter holes lasting long enough to reach the collector area. The separation distance of the two wires, then, is critical.

The reason for the marked difference in behavior of point-contact and junction transistors stems largely from their difference in construction. In the point-contact transistor, there is a large base area from which electrons may be drawn to enhance the normal collector current. The holes, traveling from emitter to collector, serve to attract these excess electrons through their strong positive field. In a comparable junction transistor, a PNP unit, the base section is quite narrow and it can supply only a limited number of electrons to the collector current. Hence, the same current-gain effect is not observed.

Point-contact-transistor Voltage and Power Gain. The current amplification which occurs in a point-contact transistor is given the special name of alpha and is represented by the symbol α. Its value ranges

between 2 and 3. By comparison, in junction transistors the value of α is less than 1, actually about 0.95. Voltage gain of a point-contact transistor is equal to the current gain times the resistance gain. In a typical unit, the emitter resistance is 300 ohms and the collector resistance is 20,000 ohms. Using these figures, we obtain

$$\text{Voltage gain} = 2.5 \times \frac{20,000}{300} \text{ (for a point-contact transistor)} = 166$$

If we compare this with a junction transistor, we see that the point-contact transistor has a much lower gain in spite of its greater current amplification. The reason, of course, is the greater resistance gain of the junction transistor.

The point-contact transistor is also capable of power gain. Power is equal to I^2R, and the current gain is 2.5. The load resistance is matched to the collector resistance, and its value falls near 20,000 ohms. Since the input impedance is about 300 ohms and the output impedance is 20,000 ohms, the resulting power gain is approximately

$$\text{Power gain} = (2.5)^2 \times \frac{20,000}{300} = 419 \text{ approximately}$$

The point-contact transistor just discussed employed N-type germanium for the base and body of the unit. It is theoretically possible to construct a point-contact transistor of P-type germanium (see Fig. 30), but commercially this has never been successfully carried out,
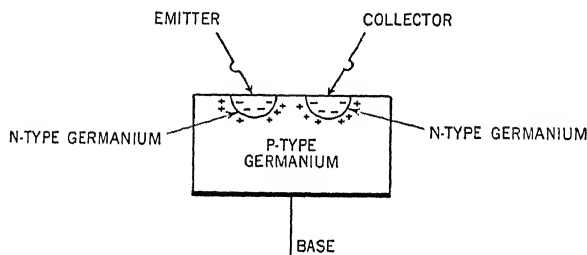
Fig. 30. A point-contact transistor using P germanium for the base.

although it has been accomplished in the laboratory. This is probably because of the inherent surface characteristics of the germanium that make the N type more stable. However, if a P-type point-contact transistor could be fabricated, its operation would be identical with the N-type point-contact transistor with the exceptions previously noted.

QUESTIONS

1. Draw a simple diagram showing how the germanium atoms are bound to one another in a crystal.

2. Since all the electrons in a germanium crystal are held fairly tightly, explain why it is considered as a semiconductor rather than as an insulator.

3. What is a hole in a semiconductor, and how is it formed?

4. How do holes travel through a semiconductor?

5. When an electric field is applied to a semiconductor, what is the effect on holes and free electrons?

6. How is N-type germanium formed? List several substances which could be employed in this process.

7. How is P-type germanium formed? List several substances which could be employed in this process.

8. Are holes ever found in N-type germanium or electrons in P-type germanium? Explain.

9. Draw a PN junction showing the donor and acceptor atoms and the free holes and electrons on their respective sides.

10. What prevents the wholesale recombination of excess holes and electrons at a PN junction?

11. What do we mean by a potential "hill"?

12. How is a battery connected to a PN junction in order to initiate a flow of current? In order to prevent current flow?

13. Explain the mechanism of current flow through a crystal diode when biased in the forward direction.

14. Draw the characteristic curve of a germanium diode. Explain the reason for the reverse current.

15. What is the Zener voltage in a crystal diode?

16. How is an NPN junction transistor formed? Label each section.

17. Describe the rules that must be followed in biasing a transistor.

18. Why must the base section be made as thin as possible in a transistor? What happens when it is made too wide?

19. Explain how a transistor operates.

20. How is gain achieved in a junction transistor?

21. Why is there no signal reversal between input and output of the amplifier shown in Fig. 21?

22. Draw the diagram of an amplifier using a PNP transistor.

23. Describe the flow of current through a PNP transistor.

24. How do point-contact and junction transistors differ in structure?

25. Describe the operation of a point-contact transistor.

26. Compare the voltage gains of point-contact and junction transistors.

CHAPTER 3

COMPARISON OF POINT-CONTACT
AND JUNCTION TRANSISTORS

Although point-contact and junction transistors possess many points of similarity, they do differ sufficiently in operation to give rise to a number of different characteristics. Perhaps the outstanding point of departure is the fact that α is greater than 1 in point-contact transistors and less than 1 in junction transistors. In spite of this, however, junction transistors will provide higher voltage and power gains because of the extremely high resistance of the collector circuit. That is, the ratio of output to input resistance in a junction transistor is so much greater than the corresponding ratio in a point-contact transistor that it more than makes up for the less-than-unity current gain.

Typical values of power gain for junction transistors range between 30 and 40 db (i.e., corresponding to power ratios of 1,000 to 10,000). For point-contact transistors, typical power gains average about 20 db (i.e., a ratio of 100).

POWER

Junction transistors excel also in their ability to handle greater amounts of power than point-contact transistors. This is tied in with the ability of the collector electrode (from which the output power is taken) to dissipate safely the heat generated by the passage of current. The contact faces between each section of a junction transistor are comparatively large, offering considerable area for the passage of current. In a point-contact transistor, the contact area between the collector and its "cat whisker" wire is on the order of only 1 square mil, and the funneling of current through an area this small causes the heat to rise rapidly. When the collector section becomes too hot, its internal resistance decreases, altering the collector bias current. Another con-

tributing factor to the low power-handling capability of the point-contact transistor is the relatively narrow path that the current follows between emitter and collector inside the transistor.

Junction power amplifiers have been built which can provide outputs of 40 watts or more, whereas point-contact transistors are largely restricted to power outputs on the order of several hundred milliwatts or less.

To aid transistors in achieving higher collector dissipation ratings, radiating fins have been added to the transistor housing (see Fig. 1). These fins help to conduct away the heat generated in the vicinity of the collector. Also useful for the same purpose are metallic housings for transistors. A power unit constructed along these lines is shown in Fig. 2.
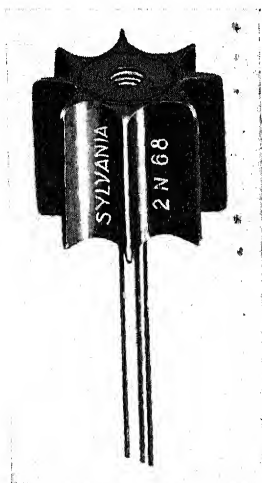
FIG. 1. A power resistor with radiating fins to help remove heat. (*Courtesy Sylvania Electric Products, Inc.*)
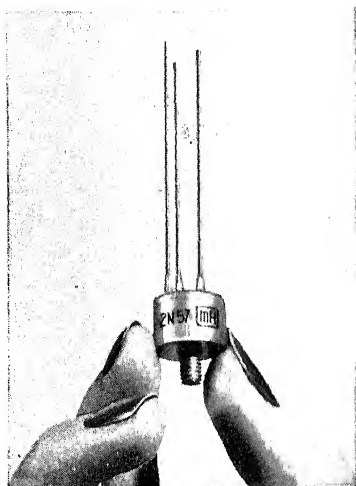
FIG. 2. A power transistor housed in a metallic container. The unit shown will provide a maximum power output of 6 watts when operated class A. (*Courtesy Minneapolis-Honeywell Regulator Co.*)

NOISE

Another place where the junction transistor has an advantage is in the matter of noise. Junction transistors have noise figures that range between 10 to 30 db, with most values falling near 20 db at the present time. The noise figures of point-contact transistors are two to

three times higher. It should be noted that the noise figures of both types of transistors are improving steadily and more and more junction transistors with noise figures near 10 db are appearing commercially.* This represents a very significant advance, since transistor noise figures are inversely proportional to frequency; i.e., transistors are noisiest in audio amplifiers, where they currently find their greatest application (see Fig. 3). By comparison, the noise factor of a 6AG5 pentode (at 1,000 cycles) is only 3 db.
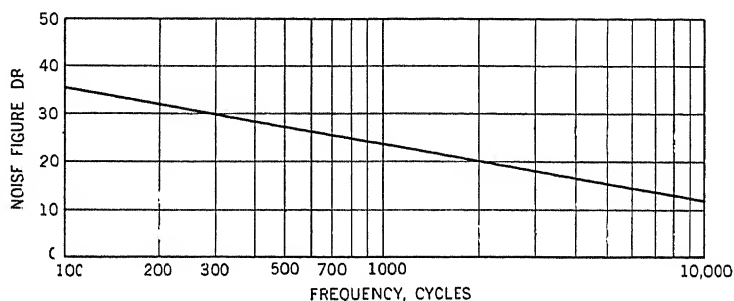
FIG. 3. The variation in noise figure with frequency for a junction transistor.

FREQUENCY RESPONSE

Before we discuss the comparative frequency responses of point-contact and junction transistors, it might be well to determine what factors control the frequency limits of a transistor. One of these is the time required for a signal to flow from emitter to collector terminals. This, in turn, depends upon the speed of the carriers within the germanium. Typical values are as follows: for electrons, about 3,600 cm per sec for each volt per centimeter of potential difference; for holes, about 1,700 cm per sec per volt per centimeter of potential difference. This means that in both point-contact and junction transistors, we cannot apply signals whose frequency changes so rapidly that the carriers (holes or electrons) will not be able to transport these changes from emitter to collector.

We have an analogous situation in vacuum tubes when the signal applied to the grid changes appreciably in the time it takes an electron to travel from the cathode to the plate. If the grid goes positive, attracting more electrons to the plate, and then turns negative before the

* The Philco SB-100 transistor, for example, has a noise figure between 4 and 6 db over the range from 100 kc to 10 Mc.

electrons reach the plate, it not only will reduce the peak number of electrons reaching the plate but also will cause them to spread out over a greater interval. (Technically, this results in phase and amplitude distortion.)

The mobility of the holes or electrons in a transistor is the velocity with which they move through the germanium when an electric field is applied. Since electrons move almost twice as fast as holes, we would expect those transistors in which electrons did most of the current carrying to have a higher frequency response than transistors which depend upon conduction by holes. Thus, consider the point-contact transistor in which N-type germanium is used (see Fig. 4a). Conduc-
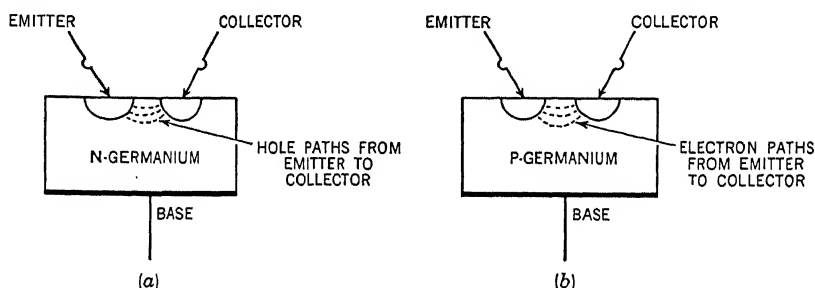
Fig. 4. Point-contact transistors using P germanium have higher frequency responses than units using N germanium. This stems from the greater mobility of electrons than of holes.

tion from emitter to collector depends upon the diffusion of holes from the emitter to the vicinity of the collector. If we constructed the same point-contact transistor using P-type germanium (as shown in Fig. 4b), the frequency response would be better because now electrons travel from emitter to collector.

In junction transistors, a similar variation exists. For the NPN arrangement (Fig. 5a), the principal current carriers are electrons; in the PNP transistor (Fig. 5b), the current carriers are holes. Hence, NPN transistors should have nearly twice the frequency response of PNP transistors.

Another factor which limits the high-frequency response is the capacitance between sections of a transistor. The higher the frequency, the lower the impedance of the shunting capacitor and the greater its shunting effect on the applied signal. This is true in both the input and output circuits, as well as between input and output.

The frequency response of a point-contact transistor can be improved by reducing the spacing between emitter and collector. It has

FLOW LINES OF ELECTRONS
IN THE EMITTER N REGION

FLOW LINES OF ELECTRONS
IN THE COLLECTOR N REGION

N   P   N

E   C

↑B

FLOW LINES OF HOLES FROM
BASE TO EMITTER N REGION

FLOW LINES OF HOLES FROM
COLLECTOR BARRIER TO BASE

········> HOLE PATHS IN P REGION   — — — ➤ ELECTRON PATHS IN N REGIONS

(a)

PATHS OF HOLES IN
EMITTER P REGION

PATHS OF HOLES IN
COLLECTOR P REGION

P   N   P

E   C

B

PATHS OF ELECTRONS IN BASE N
REGION FROM BASE TO EMITTER

PATHS OF ELECTRONS IN BASE N
REGION FROM COLLECTOR TO BASE

E_e ➤ E_c ➤

⊕ DONOR ATOM   + HOLE
⊖ ACCEPTOR ATOM   − ELECTRON

········> HOLE PATHS IN P REGIONS
— — ➤ ELECTRON PATHS IN N REGION

(b)

FIG. 5. (a) The chief carriers of current in an NPN junction transistor are electrons. (b) The flow paths of electrons and holes in a PNP junction transistor. Most of the current is carried by holes.

been found that frequency f is inversely proportional to electrode spacing in accordance with the equation

$$f \propto \frac{\rho\mu I_e}{S^3}$$

where S = distance between emitter and collector, mils
  ρ = resistivity of the germanium, ohm-cm
  μ = mobility of the holes or electrons, sq cm per volt-sec
  I_e = emitter current, amp

From this relationship we see that if we use germanium of high resistivity and small contact spacing, the frequency response will improve. Working against this is the fact that the closer the contacts come, the higher the shunting capacitance between them. Furthermore, as we shall see later, point-contact operation tends to be less stable as the germanium resistivity rises.

Figure 6 shows the effect of point-spacing variation on frequency response. Note that at spacings less than 2 mils, the high-frequency response improves rapidly.
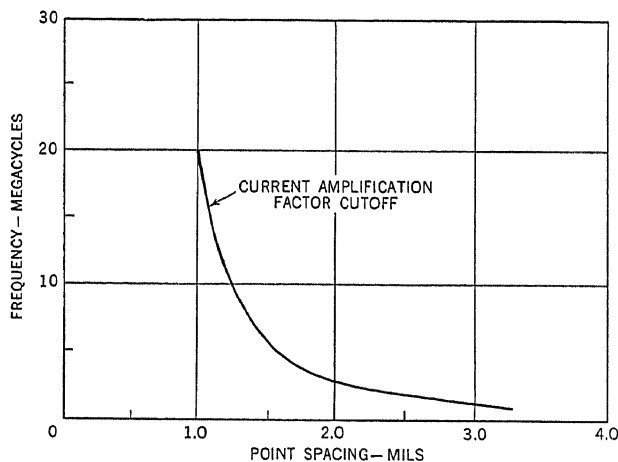
Fig. 6. Effect of variation of point spacing (in point-contact transistors) on frequency response.

In the junction transistor, the frequency response can be improved by making the central base-region layer as thin as possible. (This condition was also desirable from a current-gain standpoint.) However, one encounters manufacturing difficulties when the width is made too small. Moreover, decreasing the width of the center section serves to increase the base resistance, and the latter will degrade the voltage

gain as the frequency rises. Thus, there are a number of compromises that must be made, although as our skill in the fabrication of transistors improves, higher and higher frequency responses will become attainable.

Initially, the point-contact transistors possessed a considerable frequency advantage over junction transistors. This was due to the relative crudeness of existing manufacturing processes. The base region of the junction transistor could not be made thin enough, and this, in conjunction with the larger inherent capacitances of the transistor structure, kept the useful frequency response well below 1 Mc. In the point-contact transistor, the emitter and collector electrodes could be brought as close as 2 mils or less, while the minute area of the contacts themselves keep internal shunting capacitances to a rather low value. Hence, these transistors could be made to operate as oscillators as high as 100 Mc or more early in their development stage. However, within the past year or two, several new manufacturing techniques have evolved which have already raised the frequency limits of junction transistors by factors of 50 or more.

Alloy Junction Transistors. For example, there is the alloy junction transistor[*] that RCA has developed. This transistor is formed by diffusing indium into germanium. A relatively thick wafer of N-type germanium is taken, and a small pit is drilled into it (see Fig. 7). Then
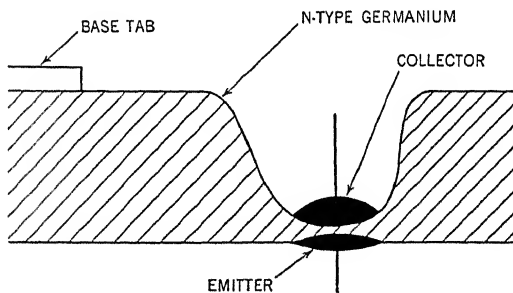
Fig. 7. Basic construction of an alloy junction transistor.

indium is placed on opposite faces of the germanium of this pit, and heat is applied. The temperature chosen is above the melting point of indium but below the melting point of germanium. The indium alloys into the germanium until the two indium-doped regions are separated by the required distance. The result is a PNP transistor (indium is an

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[*] These are also called alloy diffusion and fused junction transistors.

acceptor atom). Connections to the indium-germanium alloy emitter and collector sections are made by wires soldered to the alloy. The other ends of these wires are then spot-welded to leads that make contact to the circuit in which the transistor is placed. For protection, the completed assembly is placed in a metal or plastic case and hermetically sealed against moisture (see Fig. 8).
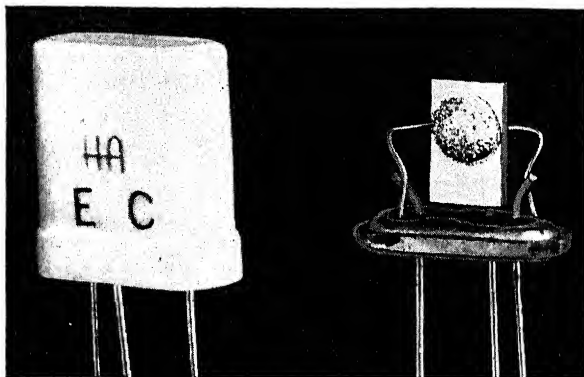
FIG. 8. The internal construction of an alloy junction transistor. The completed unit is shown at the left. (*Courtesy Hydro-Aire, Inc.*)

With the alloy diffusion method of construction, several things have been accomplished. First, the separation between collector and emitter regions is on the order of only 0.0005 in. This permits a significant reduction in transit time. Second, the base resistance is made low by the use of a relatively thick germanium wafer at all points except in the small section between emitter and collector. Also, the emitter and collector diameters (0.010 and 0.015 in., respectively) are kept small, reducing the various capacitive effects which these elements introduce. (This is independent of the diffusion process, but it does aid in improving frequency response.) Initial transistors made by this process exhibited 12 db of gain at 10 Mc. Oscillations could be sustained up to 75 Mc. With the continued improvement in the techniques of making and controlling the indium junctions, further improvements by the use of lower-resistivity germanium and by a reduction in the dimensions are made possible so that still higher frequency limits can be attained.

The diffusion, or alloy, method is feasible for both PNP and NPN junction transistors. For an NPN assembly, P-type germanium would be used and a pentavalent element would be substituted for the indium.

The Surface-barrier Transistor. Another high-frequency transistor is the Philco surface-barrier transistor.* In cross-sectional appearance (Fig. 9), this unit closely resembles junction transistors. In mode of operation, however, it represents another approach to a solid-state amplifier. In all the junction transistors thus far described, two forms of
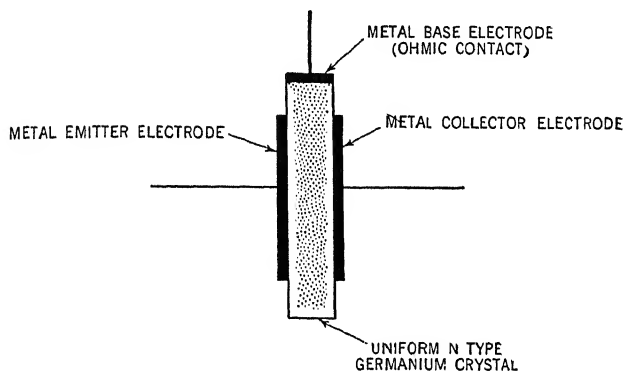
Fig. 9. Schematic cross section of surface-barrier transistor.

germanium were employed, i.e., P and N germanium. In the surface-barrier transistor, only one type of germanium is used, N germanium. Electrodes serving as the emitter and collector are plated electrolytically on opposite faces of a germanium wafer. A metal contact is then soldered to one end of the crystal and serves as the base electrode. Unlike junction transistors, the emitter and collector electrodes remain coated to the surface of the germanium. There is no penetration of the germanium lattice structure by the atoms of the metals.

To understand the operation of the surface-barrier transistor, additional facts concerning the behavior of electrons inside a crystalline structure must be known. It has been found that energy levels, or orbits, may exist on the surface of a crystal which are not found in the interior. It is believed that no orderly structure of energy bands (such as we have described in Chap. 1) exists on such a surface. Rather, the leftover bonds of germanium atoms, together with any atoms of other substances on the surface, form a two-dimensional solid with properties which are entirely different from those in the interior. It is felt that there are no forbidden bands among the surface atoms comparable to the forbidden bands found in the interior atoms. It is because of this absence that a number of free electrons move to the crystal surface and

* The Surface-barrier Transistor, a series of five papers by members of the technical staff of the Philco Research Division, *Proc. IRE,* December, 1953.

concentrate here in sufficient strength to produce a negative field which repels the free electrons of the N germanium toward the interior, causing a nearly insulating region containing a strong electric field just beneath the surface. This is the reason the N germanium in Fig. 9 is shown shaded in the interior but left unshaded in a narrow strip along the surfaces. This insulated strip is referred to as a surface barrier.

A metal electrode which is brought in contact with this germanium crystal can communicate with the main body of the crystal only through the surface-barrier region. If we apply a negative potential to the metal plate, it will further repel the interior electrons away from the surface and cause the intervening layer to become thicker. Making the metal electrode positive will attract these interior electrons and reduce the width of the insulating layer. Current flow between the surface electrode and the inner portion of the crystal can thus be made smaller or larger, as desired.

To form a transistor with the N germanium, we require an appropriate distribution of holes which will travel from emitter to collector as they do in a comparable PNP junction transistor. In the surface-barrier transistor it is found that a population of holes exists just under the germanium surface. These arise from the valence electrons that are thermally excited enough to leave their atoms and move into some of the energy levels at the surface which are intermediate between the conduction band and the valence band. These electrons come from the atoms located near the surface, and for every such electron departure, a hole is created. This action is confined to the atomic layer just below the surface; the rest of the germanium interior produces relatively few holes.

Some metal contacts produce a denser hole population under the surface of the germanium than others. The most useful metals for this purpose are indium and zinc.

In review, then, we see that the surface-barrier transistor owes all its characteristics to the special conditions which exist at the surface of a crystalline structure. The strong electronic field at the surface forces free electrons to remain in the interior. Also, because of the presence of intermediate energy levels at the surface, holes are found concentrated just below the surface. When a metal contact to the crystal is made positive, it repels these holes through the barrier. This would be the emitter electrode. The other electrode, the collector, is reverse-biased (i.e., biased negatively), and holes coming within its field after passage through the germanium will be drawn to the surface.

The surface-barrier transistor thus consists of a germanium crystal

which forms the base plus two metal electrodes, on opposite faces of the crystal, which serve as the emitter and collector electrodes.

A positive emitter will drive the holes toward the collector, but at the same time it will attract the interior electrons. For efficient transistor operation, the electron current should be reduced as much as possible, since only the hole current is received at the collector. This was achieved by bringing the collector electrode within 0.0002 in. of the emitter. The negative charge on the collector drives the germanium free electrons away from the emitter, while, at the same time, it presents a greater attractive force for the holes.

To achieve the minute spacing required, a process of "electrolytic machining" was employed. Two tiny jets of a metal-salt solution are directed from miniature glass nozzles toward opposite faces of a germanium wafer, with the latter serving as the anode and electrodes in the glass nozzles serving as the cathodes. This action etches away the germanium under each jet until the desired amount of material has been taken away. Then the voltage polarity is reversed, and now the same jets are made to electroplate the metal ions of the salt solution directly upon the freshly etched surface of the germanium (see Fig. 10). This forms the desired emitter and collector electrodes. This is a

N-GERMANIUM CRYSTAL

ELECTROPLATED EMITTER
(0.005 INCHES DIAMETER)

ELECTROPLATED COLLECTOR
(0.007 INCHES DIAMETER)
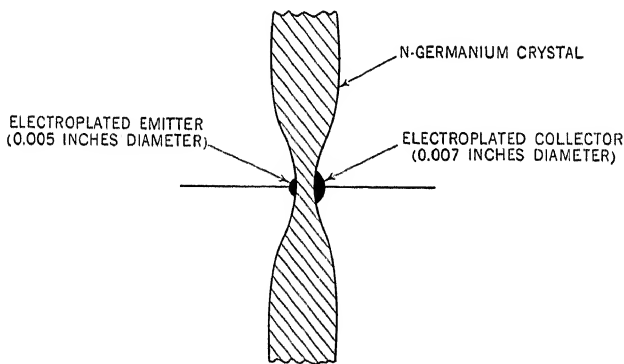
Fig. 10. Detail of surface-barrier transistor cross section.

very efficient and ingenious method of using the salt solution to accomplish both actions of etching and electroplating. Diameter of the emitter is 0.005 in., and that of the collector, 0.007 in.

With the surface-barrier transistor, video amplifiers of 5-Mc bandwidths have been built and tuned amplifiers at 30 Mc have shown stage gains of 15 db or more. Also, reliable oscillator operation up to 70 Mc has been attained.

Other methods for improving the high-frequency operation of transistors have been described in the literature,* but only the two units discussed above have appeared commercially.

Recently a gaseous diffusion method of producing germanium (and silicon) transistors has been developed which gives promise of raising the frequency limits well into the megacycle region. The method is described on page 242.

CUTOFF FREQUENCY

The frequency characteristic of a transistor is given in terms of a cutoff frequency. This is defined as the frequency at which α drops to a value which is 0.707 (i.e., 3 db) below its low-frequency value. The low frequency usually employed as a reference is either 1,000 or, more recently, 270 cycles.

It will be found that transistors will operate as oscillators at much higher frequencies than the indicated cutoff frequency. On the other hand, for amplification, a transistor having a 3-db drop in the current-amplification factor (i.e., α at 5 Mc) may have a significant reduction in voltage or power gain at 2 Mc or less. Thus it is frequently necessary to restrict the operation of a transistor well below its rated cutoff frequency.

At the present time, junction transistors find their widest application as audio amplifiers and in the r-f and i-f stages of a-m broadcast receivers. Point-contact transistors are used principally as higher-frequency oscillators. Undoubtedly a broadening in these areas of application will take place as the techniques of transistor manufacture improve.

TEMPERATURE EFFECTS

The ability of properly processed germanium to serve as a transistor depends wholly on the electronic bonds and lattice structure existing within the germanium crystal. It was noted previously that too high a concentration of impurities will increase the conductivity of the germanium to such an extent that the effectiveness of the emitter in controlling collector current is destroyed. Conductivity will rise also with temperature. An increase in thermal energy will lead to more broken covalent bonds, more free electrons and holes, and a greater current flow in both input and output circuits for the same applied voltages. This, in turn, will reduce control of the collector circuit by the emitter, practically nullifying the transistor action in the germanium. It is even

* One promising method was described by J. M. Early, P-N-I-P and N-P-I-N Junction Transistor Triodes, *Bell System Tech. J.*, May, 1954.

possible for the thermal action to feed on itself, eventually destroying the transistor completely. The higher temperature results in more current, which raises the temperature even higher, which results in more current, etc., until the entire unit is permanently damaged.

Because of this sensitivity to temperature, great care must be taken to see that the specified maximum operating temperature is not exceeded. In transistor characteristics charts, the maximum collector dissipation is specified at a definite temperature (such as 25, 40°C, etc.). If the operating temperature exceeds this value, then it becomes necessary to lower the collector-dissipation rating. For example, Sylvania indicates that the maximum dissipation rating should be derated (i.e., lowered) 1 mw for each degree centigrade increase in ambient temperature. Thus, if the maximum rating for a certain transistor is 50 mw at 25°C, then at 30°C, the maximum rating is only 45 mw, etc.

Sometimes two maximum ratings will be given: one, the lower one, in free air; the other, when the transistor is mounted flush against a metallic surface (such as an aluminum chassis) which will conduct the heat away. The technical name for these heat conductors is "heat-sink," and they can make an appreciable difference in the maximum dissipation rating. The Sylvania 2N95 NPN junction transistor has a collector-dissipation rating in free air of 2.5 watts and a rating of 4.0 watts when mounted flush against an aluminum chassis. This is a significant point to keep in mind, particularly when the transistor is to be operated near its maximum rating.

LIFE EXPECTANCY

An important consideration in the application of any electronic device is its life expectancy. How long will this component last under normal operating conditions? In the case of transistors this is an especially pertinent question, since, they, like tubes, form a vital link in a circuit.

One of the most important factors which governs the life of a transistor is its resistance to moisture. Moisture and other chemical agents tend to degrade transistor action, and some means of protection must be incorporated in transistor manufacture. Most frequently used is the method whereby the transistor is hermetically sealed in glass and metal housings which can withstand a variety of adverse conditions. So effective are these protective shields that transistors have been able to withstand immersion in water for long periods of time with practically no noticeable effect on operating efficiency. They have also withstood centrifugal forces with accelerations as high as 31,000 times the

force of gravity and impact tests with accelerations as high as 1,900 times the force of gravity. This is greatly in excess of the forces which will completely shatter any vacuum tube.

When a transistor is properly constructed and used, it will be found that failure will occur gradually over a long period of time. The deterioration will show up in reduced gain, lowered collector resistance, and a higher I_{co}. The latter notation stands for the current that flows in the collector circuit, under normal reverse bias, when the emitter current is zero. This collector current is due to the presence of minority carriers in both the collector and base which have broken their bonds through the absorption of light and thermal energy. High I_{co} is undesirable because it dissipates energy which might otherwise be employed by the signal. More will be said on I_{co} in the chapter on amplifiers.

Once transistors have been properly tested and found to be good, it will seldom happen that an open circuit will be subsequently encountered. It is more likely that open-circuited transistors will be found among units coming from the factory. On the other hand, if a transistor is permitted to operate under overload, it is entirely possible that a short circuit will develop. This is said to arise from the diffusion of impurities from the collector to the base region under the effects of the overload heat. The result, if this diffusion is extensive, is to destroy the junction and, with it, the transistor.

Transistors are too new a development to have enabled us to gather sufficient data concerning their full life span. However, it is confidently expected that they can be made to last more than 70,000 hr, either on the shelf or in operation. This means that a transistor might operate continuously for 8 years—a period far greater than what we can now reasonably expect from all but a very few specially made vacuum tubes. (Specifically, the tubes Bell Telephone is placing in the undersea coaxial cables have an estimated life of 40 years.)

TRANSISTOR SYMBOLS

Circuit symbols for transistors are still somewhat in a state of flux, although the point has been reached where one will see fewer and fewer variations. The basic symbol for a transistor is shown in Fig. 11. The emitter element has an arrowhead, the base is a straight line, and the collector element is shaped like the emitter, but it possesses no arrowhead. This symbol is used for both point-contact and junction transistors and, like the tube symbol, may be placed in any position.

To distinguish between NPN and PNP transistors, the method shown in Fig. 12 is employed. If the emitter is a P-type germanium, the arrowhead is directed in toward the base. On the other hand, if N-type germanium is used for the emitter, the arrowhead points away from the base. This particular custom is not yet universally followed, so the reader is cautioned to check the applied bias polarities. These are the most positive indicators.
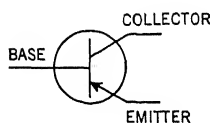
Fig. 11. The schematic symbol for a transistor.
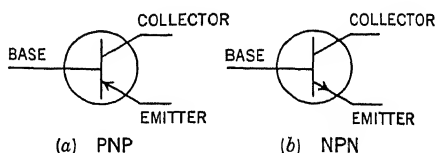
Fig. 12. To distinguish between PNP and NPN transistors, the method shown is employed frequently. This notation will be followed in this book.

Three minor variations that have been employed are shown in Fig. 13. Their use is not extensive, and actually they would not cause any confusion. In addition, there are other types of transistors and where their form differs significantly from the transistors discussed, other sym-
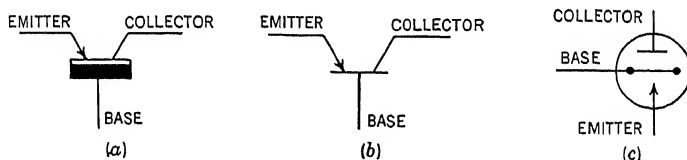
Fig. 13. Three additional symbols that have been employed to represent transistors.

bols are used. A number of these transistors are examined in Chap. 8, and appropriate symbols will be given there.

COMPARISON WITH VACUUM TUBES

Transistors are designed to perform the same functions as vacuum tubes, and it is therefore only natural to want to compare the two electrically to see where they differ and where they are similar. As a first step, let us consider these two components in the light of their internal operation. In a transistor, current flow through the various germanium sections is initiated by the flow of electrons or holes from the emitter

section. In a vacuum tube, this initiation starts at the cathode. Thus we could say that the emitter in a transistor is equivalent to the cathode in a vacuum tube. (The word emitter, of course, is a clue to the function of this element.)

The recipients of this current flow are the collector in the transistor and the plate in the vacuum tube. Hence these two elements can be considered to be equivalent in their actions. This still leaves the grid in the vacuum tube and the base in the transistor, and the equivalence of these elements is seen in the fact that whatever current flows from emitter (or cathode) to collector (or plate) must flow through the base (or grid) structures. Current flow in both devices is governed by the potential difference between emitter or cathode and base or grid.

Figure 14 illustrates these analogies between transistor and vacuum tube.

Fig. 14. Comparable elements in tubes and transistors: grid-base, cathode-emitter, plate-collector.

The next step is to consider both devices in terms of the d-c voltages which are applied to their elements. In a vacuum tube, the grid is practically always biased negatively with respect to the cathode. This makes the grid impedance very high (except at high frequencies, where other effects enter the picture). The plate, on the other hand, is always given a potential which is positive with respect to the cathode. The purpose of the plate is to attract the electrons emitted by the cathode, and since electrons possess a negative charge, a positive potential is needed to attract them.

In the transistor, conditions are somewhat different, though we wish to accomplish the same purpose. To initiate a flow of current, there must first be a flow of current between emitter and base and the bias battery must be connected to produce that current flow. This is what determines the polarity connections of the bias battery. If the emitter is formed by P-type germanium, the base will contain N-type germanium and current flow will occur between these sections when the positive battery terminal connects to the P-type emitter and the nega-

tive battery terminal to the base. We have spoken of this as forward biasing, and under these conditions the impedance of the emitter circuit is low. Here, then, is a marked departure from conventional amplifier practice as we know it now. In every transistor, the emitter-to-bias circuit is *always* biased in the forward direction.

When we employ N-type germanium for the emitter and P-type germanium for the base, then we must reverse the battery connections if we are to obtain the desired current flow through the emitter. Thus, the guiding thought in the emitter circuit is current flow, and we alter the battery conditions to suit the type of germanium being used in order to achieve this objective. Here is a radical departure from anything we have known in vacuum-tube practice, and it points up something which we have hinted at throughout the preceding discussion. That is, transistors are current-operated devices, while vacuum tubes are voltage-operated. α, for example, is the symbol representing the ratio of $\Delta I_c / \Delta I_e$, where ΔI_c is the change in collector current for a change in emitter current ΔI_e. The counterpart of this symbol in the vacuum tube is μ, the ratio of a voltage change in the plate circuit produced by a voltage change in grid circuit. Again we see the emphasis on voltage in a tube as against current in the transistor.

In the collector circuit, the proper battery biasing is such that the current flow is reduced to a minimum. (Note that it is not zero, although it is only on the order of microamperes.) This is known as reverse biasing and is always true with collectors. To attain this condition, we must connect the battery in accordance with the type of germanium used in the transistor. If the collector is formed of P-type germanium and the base has N-type germanium (in a PNP junction transistor), then the negative terminal of the battery goes to the collector and the positive terminal to the base. Conversely, if the collector has N-type germanium and the base P type, the reverse is true. Great care must be observed when connecting the collector battery because biasing in the forward direction may cause so much current to flow through the collector-base sections that the resulting heat will permanently damage the transistor and render it unfit for further use. The excess current flow is due to the higher potential of collector batteries. While the applied emitter voltage is generally less than 1 volt, the applied collector voltage can be as high as 22½ volts. A junction biased in the forward direction with this high a voltage will receive enough heat from the ensuing current to be permanently affected.

In a vacuum tube, no similar condition exists and we have never had to observe this precaution.

BASIC TRANSISTOR AND VACUUM-TUBE
AMPLIFIER CIRCUITS

All vacuum-tube amplifiers can be divided into three classifications: grounded cathode, grounded grid, and grounded plate. A similar division exists for transistor amplifiers: grounded emitter, grounded base, and grounded collector. In the sections to follow, the basic differences among each group will be examined. Further elaboration will then be made in the succeeding chapters dealing with applications.

Classifying vacuum-tube amplifiers in terms of grounded cathode, grounded grid, and grounded plate is a practice that has recently begun to gain favor among workers in the field. The term grounded-grid amplifier is not particularly new, but it has not been common practice to call the conventional amplifier a grounded-cathode amplifier or the cathode follower a grounded-plate amplifier. Yet when you stop to think about it, that is precisely what these amplifiers actually are.

Consider, for example, the conventional amplifier circuit shown in Fig. 15a. The input signal is applied to the grid, while the output signal is taken from the plate. The cathode usually possesses a resistor in its circuit, but the resistor is bypassed in most applications by a capacitor that is frequently large enough to place the cathode at ground potential in so far as the signal is concerned. Under these conditions, the cathode need not be at ground potential with respect to a d-c voltage and, indeed, usually has some positive voltage on it because of the voltage drop across the cathode resistor. However, signalwise, the cathode is at ground potential. This, then, is a grounded-cathode amplifier.

Note the situation does not change if the cathode is returned to some positive or negative d-c voltage, as in Fig. 15b, instead of to ground. In this instance, we have simply changed our reference point from one d-c voltage (zero) to another d-c voltage which may be higher than zero (i.e., positive) or lower than zero (i.e., negative). Amplifier operation, however, remains the same. Whatever the polarity of the d-c voltage chosen, this is still the point from which the other d-c voltages on the tube are measured.

The above designation remains the same even when a cathode bypass capacitor is not employed. This simply has the effect of introducing some inverse feedback. The signal input and output points are unaltered, and the cathode is still common to both input and output circuits.

The key word in the last sentence is the word "common." The more general definition of a grounded-cathode amplifier is one where the cathode is common to both input and output circuits. Hence, the name common cathode is interchangeable with grounded cathode, and both
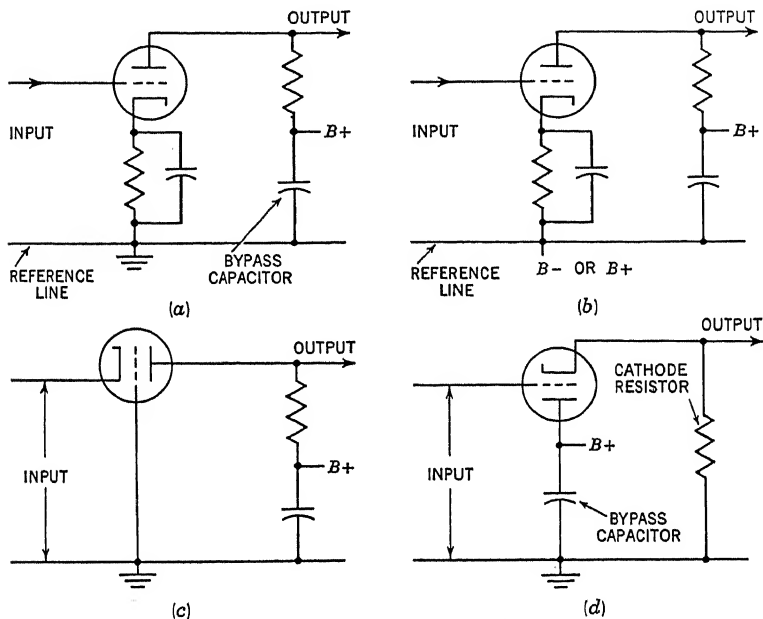
FIG. 15. (*a*) Grounded- or common-cathode amplifier. (*b*) Same amplifier with cathode returned to a d-c reference voltage instead of to ground. (*c*) Grounded- or common-grid amplifier where grid is common to both input and output circuits. (*d*) Grounded- or common-plate amplifier. If the last stage appears strange, turn it around and the familiar cathode follower will be immediately evident. The amplifiers have all been drawn in the manner shown to bring out the reason for their indicated designations.

will be used throughout the book. The same applies to grounded-grid (or common-grid) and grounded-plate (or common-plate) amplifier.*

In a grounded-, or common-, grid amplifier (Fig. 15*c*) we place the grid at signal ground while the input signal is applied to the cathode and the output signal is obtained at the plate. Again, note that the grid

* The word ground, in nearly all its applications in electronics, should more frequently be considered in its general sense of being a reference point common to one or more circuits. The beginner in electronics is often led to believe that ground possesses special properties not found in other portions of the circuitry. Ground is best regarded as just another conductor which derives any special qualities it may have only by virtue of the fact that it is common to several circuits. The notation common-base, common-emitter, and common-collector amplifier is also widely used.

may have some d-c voltage on it, for biasing purposes, without affecting the designation or operation of the stage.

The final arrangement, grounded, or common, plate, is shown in Fig. 15d. Here the plate is returned to signal ground, while the input signal is applied to the grid, and the output signal is obtained at the cathode. The best known name for this amplifier is cathode follower.

Each of these amplifiers possesses its own characteristics stemming from the method of connection. For example, the grounded-cathode amplifier will provide the greatest voltage and power amplification, while the grounded-plate amplifier will provide the least. On the other hand, the grounded-plate amplifier is best suited to provide a match between high- and low-impedance systems. Each has certain characteristics which make it the most desirable arrangement for certain applications. It will be found that the same is true of transistor amplifiers.

Grounded-base Amplifier. It is convenient to start first with a grounded-base transistor amplifier. This is shown in Fig. 16a. The input signal is applied to the emitter, and the output signal is obtained at the collector. The equivalent vacuum-tube amplifier is shown in Fig. 16b. The grid, being equivalent to the base, is grounded. The signal is then fed to the cathode; the plate is the output circuit.
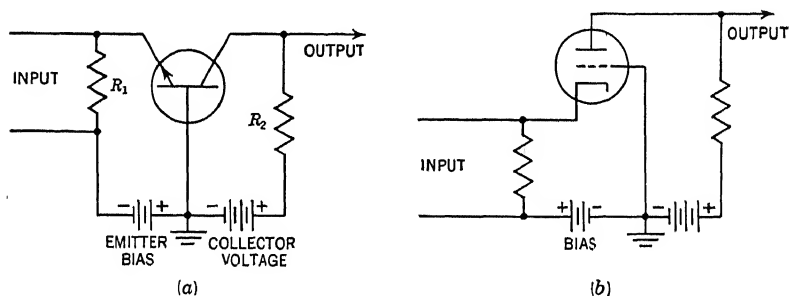
FIG. 16. (a) A grounded-base transistor amplifier and (b) its analogous grounded-grid vacuum-tube amplifier. The polarity of the voltages used in the transistor circuit will be governed by the type of germanium used for the various elements. Here an NPN transistor is shown.

In a grounded-grid amplifier, the input and output signals possess the same polarity. That is, passage through the tube does not alter the phase of the signal. In a grounded-base transistor amplifier, the same behavior is found. To illustrate this, the amplifier of Fig. 16a has been drawn using an NPN transistor and the battery polarities have been

chosen accordingly. Assume, now, that the incoming signal is positive at this instant. This positive voltage will counteract some of the normal negative bias between emitter and base and serve to reduce the current flowing through the transistor. This, in turn, will reduce the voltage drop across R_2, making the collector potential more positive. Thus, a positive-going input signal produces a positive-going output signal.

During the negative half cycle of the input signal, the emitter will be driven more negative than it normally is with respect to the base. This will increase the flow of electrons (here) from emitter to collector and cause the negative voltage drop across R_2 to increase. This will drive the collector more negative. Again we see that the polarity of the output signal is similar to that of the input signal.

The input impedance of a grounded-base junction transistor amplifier is low, with values of 100 to 300 ohms being typical. Point-contact transistors have higher input impedances generally than junction units. The output impedance of a grounded-base junction transistor is quite high, being on the order of 500,000 ohms. On the other hand, the output impedance of a point-contact transistor amplifier under similar conditions is only moderate, seldom exceeding 10,000 ohms, and frequently it is lower than that.

The junction transistor provides higher voltage and power gains than point-contact amplifiers employing the grounded-base arrangement. Average values of junction voltage and power gains are 150 and 400, respectively, compared with 30 and 100 for the point-contact transistor.

The grounded-base arrangement is most frequently employed for point-contact transistors because in the other arrangements to be described, the point-contact unit tends to be unstable, leading to oscillations and erratic behavior.* Junction transistor amplifiers are stable in the grounded-base connection, but better power gain can be secured with a grounded emitter, and this is the arrangement most frequently employed.

Grounded-emitter Amplifier. The grounded-emitter amplifier (Fig. 17a) is the most popular of the three groups. The input signal is applied to the base, and the output signal is obtained at the collector. The equivalent vacuum-tube amplifier is shown in Fig. 17b, and the reader will immediately recognize this as the most common amplifier in use today.

* The reason for this instability is discussed later in the chapter.

It turns out, when the mathematics of grounded-emitter circuitry is worked out, that this arrangement possesses a number of advantages for the junction transistor over the grounded-base approach. For one thing, the input impedance is higher, averaging between 700 and 1,000
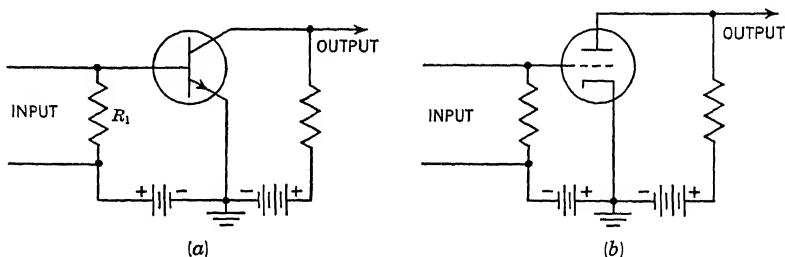
FIG. 17. (a) A grounded-emitter amplifier and (b) its vacuum-tube counterpart. An NPN transistor is used in a; for a PNP transistor, the polarities of the batteries would have to be reversed.

ohms. Output impedance is lower than in the grounded-base connection and most frequently falls around 50,000 ohms or less. However, the power gain is found to be on the order of 5,000 or more. (Voltage gain can be considered to be about the same for both types of connections.) Another surprising fact is that current gain has also increased, this time beyond the value of 1. With both these attributes, the popularity of the common-emitter arrangement is understandable.

At this point the reader may wonder about the statements made in the preceding paragraph. For example, power gain is said to have gone up in spite of the fact that the input resistance has increased and the output resistance has decreased. Then there is the current gain and the fact that this is greater than 1, although we are still dealing with a junction transistor where α was shown to be less than 1. Actually, the two effects are closely related and are. tied in with a reevaluation of the definition of current gain for common-emitter connections. This is best attempted after we have examined the characteristic curves of transistors later in the chapter. In the meantime, the reader is asked to accept this data as given.

The point-contact transistor is seldom used in the grounded-emitter configuration because it is inherently unstable. Equationwise this shows up as a negative resistance in the input and output circuits and, as such, is extremely useful in an oscillator where this negative resistance can offset or counterbalance a positive resistance in a resonant circuit, enabling the circuit to oscillate freely. Hence, we shall meet grounded-emitter circuits using point-contact transistors in

the chapter on oscillators; we shall seldom, if ever, meet them in amplifiers.

An interesting feature of the grounded-emitter form of connection is that fact that a phase reversal occurs as the signal passes through the stage. In this it is similar to its vacuum-tube prototype, the grounded-cathode amplifier.

The reason for the reversal can be understood by considering the amplifier shown in Fig. 17a. The base-emitter circuit is biased in the forward direction, with the negative side of the bias battery connecting to the emitter and the positive side of the battery to the base. (In this way, the negative battery terminal repels the excess electrons in the N-type emitter toward the PN junction while the positive battery potential drives the holes in the base to the same junction.) If, now, we apply a signal to the base, here is what will happen.

When the signal is negative, it will tend to reduce the bias potential applied between emitter and base. This means that the electrons in the emitter and the holes in the base will have less compulsion to over-come the inherent separating force at the junction and less current will flow. This, in turn, will reduce the collector current, providing less voltage drop across the load resistor. As a result, potential at the top end of R_2 will become more positive.

During the positive half cycle of the signal, the total voltage in the emitter-base circuit will rise. This will increase the flow of current through the emitter, the collector, and R_2. The increased voltage drop across R_2 will make the top end of this resistor more negative. Thus, in grounded-emitter amplifiers, the output signal is 180° out of phase with the input signal. This is true of both junction and point-contact transistors.

Grounded-collector Amplifiers. The final transistor amplifier circuit arrangement is the grounded collector. This is shown schematically in Fig. 18 together with its vacuum-tube counterpart. Note that the plate of the vacuum tube is not d-c grounded, since this element still requires a positive potential (relative to the cathode) in order to attract electrons. However, the plate is at a-c ground by virtue of the large bypass capacitor, and that is actually what we are interested in.

The grounded-plate vacuum-tube amplifier will be recognized as the familiar cathode follower. It possesses a high input impedance between cathode and grid and a low output impedance. Voltage gain of this arrangement is always less than 1. In the grounded-collector arrangement we find many of the same characteristics. Thus, the input impedance, base to collector, is very high because of the reverse bias-

ing of the collector. Typical values range between 300,000 and 600,000 ohms. The output impedance, on the other hand, is low, frequently falling below 100 ohms. And to complete the analogy, the voltage gain of a grounded collector is always less than 1. Thus, here we have the transistor equivalent of the vacuum-tube cathode follower.
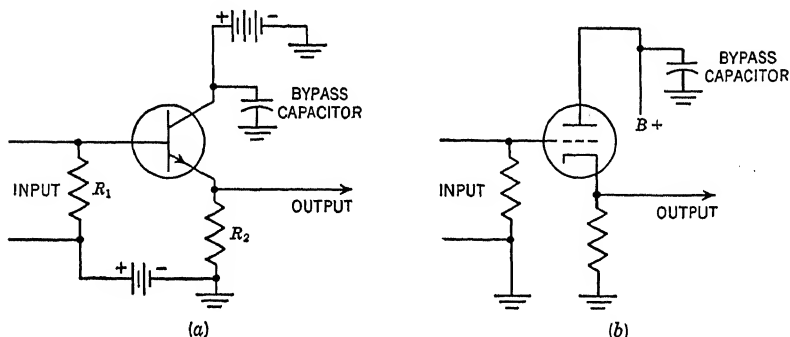
FIG. 18. A grounded-collector amplifier (*a*) and its vacuum-tube counterpart (*b*). The cathode resistor in *b* would have a fairly high value.

Phase reversal of the signal does not occur in this stage. Any signal applied to input will appear at the output with the same phase. Junction grounded-collector circuits are stable, but point-contact stages have a negative output impedance. Again this characteristic might be desirable in an oscillator, but it would lead only to instability in an amplifier.

An interesting feature of the grounded-collector circuit is its ability to pass signals in either direction, enabling it to function as a two-way amplifier. This does prove very useful under some conditions.

Note that no matter how a transistor is connected, the method of d-c biasing remains unaltered. The emitter is *always* biased in forward direction, while the collector is *always* biased in the reverse , or high-resistance, direction.

TRANSISTOR CHARACTERISTIC CURVES

The difference in operation between transistors and vacuum-tubes, i.e., that one stresses current while the other voltage, is reflected in the characteristic curves of these two devices. In the characteristic curves for a 6AG5 pentode (Fig. 19) the plate-current–plate-voltage curves are given for a series of grid-voltage values. The corresponding set of curves for a transistor are given in Fig. 20. Here, collector volts and

collector currents are plotted for various values of emitter current. Note the great similarity between these two sets of curves. In the case of the 6AG5 pentode, the plate current is relatively independent of the plate voltage from approximately 50 volts on. The only factor that determines plate current is grid voltage. For the transistor, collector current is likewise independent of collector voltage and is wholly a function of emitter current. This is understandable, since the collector current is that portion of the emitter current which is not drawn by the base.
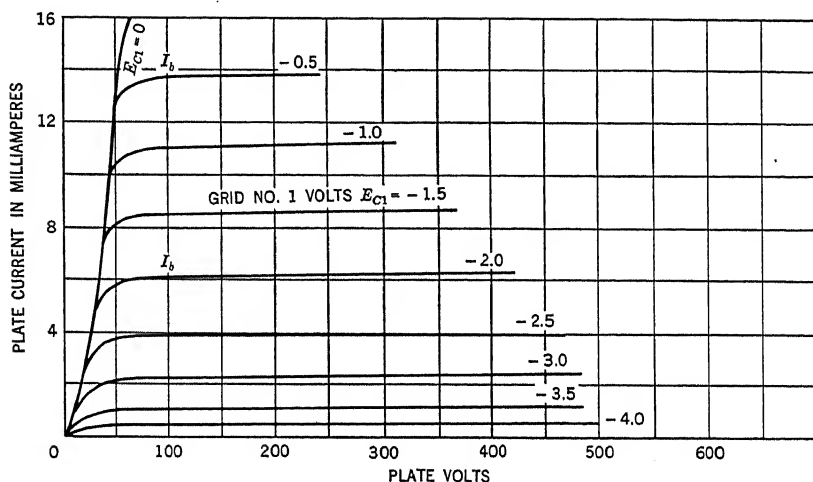
FIG. 19. The E_p-I_p characteristic curves for a 6AG5 pentode vacuum tube.

An interesting feature of the transistor characteristic curves is the fact that when we reverse the collector voltage (as we do at the left-hand side of the chart), the collector current drops sharply to zero and then, if the chart had extended down, would have rapidly reversed itself and started flowing in the opposite direction (i.e., the forward direction). The latter condition is not desired, since it would quickly lead to excessive current flow, with overheating and permanent damage to the crystal.

In the plotting of graphs, it is customary to place the more important (i.e., the independent) variable along the horizontal axis. This should be done with the transistor curves, placing the collector-current axis horizontally and the collector-voltage axis vertically (see Fig. 21). In practice both types of presentations will be found, with perhaps greater emphasis given to the form shown in Fig. 20 because of its correspondence to the more familiar vacuum-tube curves.

It is not uncommon to find collector-voltage values listed with negative values in these characteristic charts. This is to indicate that the applied collector voltage is negative in polarity, such as we would use with a PNP transistor. For an NPN transistor, the collector voltage would be positive.
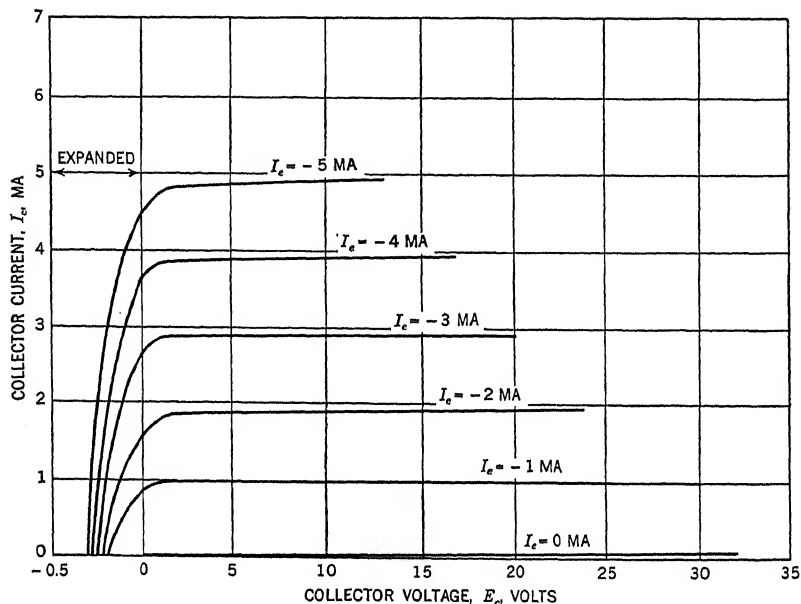
FIG. 20. The characteristic curves for a type 201 NPN junction transistor. (*Courtesy Texas Instruments, Incorporated.*)

Negative signs are also found in front of the current figures, and here their presence is associated with the direction of collector-current flow in relation to the conventional method of current flow through a circuit. Conventionally, electric current is taken to flow from the positive side of a voltage source through the circuit to the negative side. ·Electron flow, with which most technicians are familiar, travels in the opposite direction. Because of this difference in treating current direction, it is suggested that any negative signs appearing in front of collector-current values be ignored. As long as the proper battery polarity is applied to the collector, the current will take care of itself.

Most manufacturers, when they give transistor characteristics, include the output characteristic curves for the grounded-base and grounded-emitter connections. Thus, the curves in Fig. 20 are for the grounded-base connection. A similar set of curves for the same tran-

sistor connected as a grounded emitter are shown in Fig. 22. Note that in the latter set of curves, the collector voltage has a greater effect on collector current, indicating that the collector resistance is not so high as it is in the grounded-base connection. This difference we have already noted.
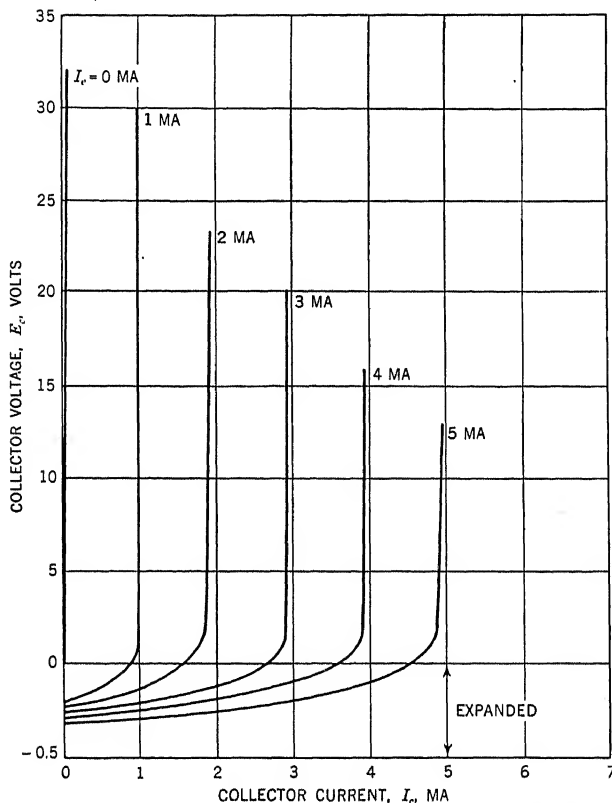
Fig. 21. The same curves shown in Fig. 19 with the collector-current values plotted horizontally and the collector voltages plotted vertically. Both types of presentations will be found in the literature.

However, it was also indicated at that time that although the collector resistance was less, still the grounded-emitter connection provided a greater power gain. We are now in a position to determine the reason for this behavior.

When the base is grounded, the incoming signal is applied to the emitter and the output signal is taken from the collector. Voltage gain is given by

$$\text{Voltage gain} = I \text{ gain} \times R \text{ gain}$$

Current gain is the ratio of I_c (the collector current) to the emitter current I_e and ranges about 0.95. We have an over-all voltage gain because the collector resistance is much greater than the emitter resistance.

When the transistor is connected with the emitter grounded and the input signal is applied to the base, then the I gain portion of the above equation represents the ratio

$$\frac{\text{Change in collector current}}{\text{Change in base current}} = \frac{\Delta I_c}{\Delta I_b}$$

Note that we are no longer interested in the emitter current or what a change in this current will do to the collector current. Now our attention is directed to the base current. Accordingly, if you examine the characteristic curves for a transistor with a grounded emitter (Fig. 22), you will see that the collector-voltage–collector-current curves are given for various values of *base* current rather than of emitter current.

The special symbol α (alpha) was used to represent the ratio

$$\frac{\Delta I_c}{\Delta I_e}$$

FIG. 22. The characteristic curves for the type 201 NPN transistor connected as a grounded emitter. (*Courtesy Texas Instruments, Incorporated.*)

and in a corresponding manner, the symbol β (beta) is used to represent

$$\frac{\Delta I_c}{\Delta I_b}$$

In contrast to α values, which are invariably less than 1 for junction transistors, β values are always greater than 1 and commonly range as high as 50 or more. These high values stem from the fact 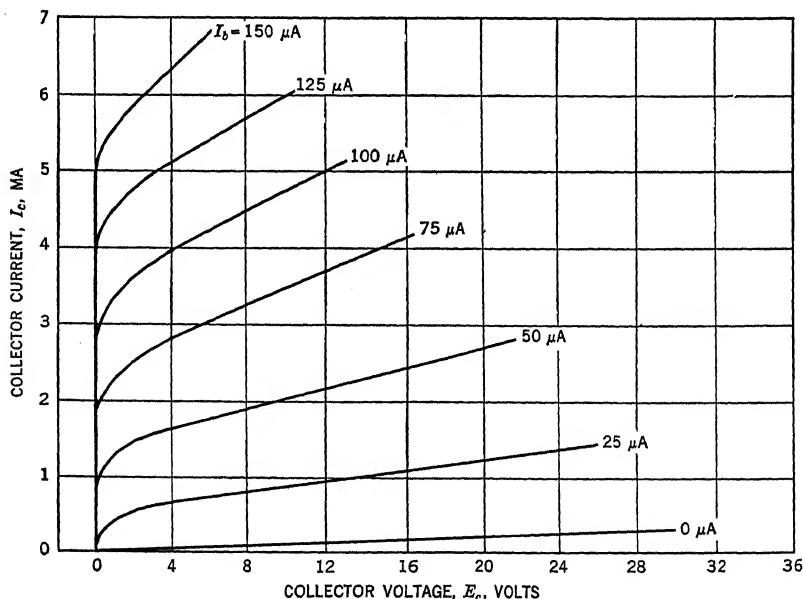that the base current is very small (being the difference between collector and emitter currents) and to produce a significant change in the base current requires a considerably larger change in collector current.

β values are frequently given in transistor characteristics data charts. β can also be computed directly from the curves of Fig. 23b. For example, at a collector voltage of 5 volts, a change in base current from 50 to 100 μa produces a change in collector current from 0.5 to 1 ma. Or

$$\beta = \frac{1 \text{ ma} - 0.5 \text{ ma}}{100 \, \mu\text{a} - 50 \, \mu\text{a}} = \frac{0.5 \times 10^{-3} \text{ amp}}{50 \times 10^{-6} \text{ amp}} = 10$$

In the data listing, the manufacturer of this transistor states that the beta current-amplification factor has a minimum value of 9. Thus, even though the resistance gain of a junction transistor with emitter grounded is less than the resistance gain for the grounded-base arrangement, the current gain with the former is so much higher than the latter that the power gain is increased considerably.

β is related to α for grounded-emitter arrangements by the equation

$$\beta = \frac{\alpha}{1 - \alpha}$$

It is seen that the closer α is to 1, the larger β becomes.

TYPICAL TRANSISTOR DATA

An indispensable tool for anyone dealing with the design, operation, or service of electronic equipment is a tube manual. Here we find the mechanical and electrical specifications for each type of tube, plus a set of characteristic curves. In similar fashion, equivalent data is published by transistor manufacturers for each of their products.

Examples of such data are given in Table 1 for the Raytheon CK722 PNP junction transistor and in Table 2 for the Texas Instruments, Incorporated, 200 NPN junction transistor. In the data for the CK722, the mechanical specifications are listed first. This includes the type of housing, the base (or lack of it), and the manner of identifying the

Table 1. Characteristics of Raytheon CK722 PNP Junction Transistor

Mechanical Data

Case .... Plastic and glass

Base .... None (0.016-in. tinned flexible leads, 1.5 in. minimum length, spaced 0.008 in. center to center)

Terminal connections ... Lead 1: collector
Lead 2: base
Lead 3: emitter

Mounting position ...... Optional
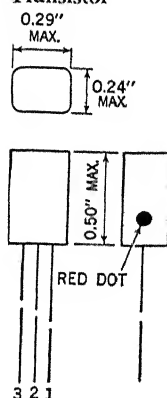
Electrical Data

	Ratings, absolute maximum	Average character-istics (at 27°C)	Average characteristics (at 27°C)		
			Common emitter	Common collector	Common base
Collector voltage, volts	—22	—6	—1.5 to —6	—6	—6
Peak collector voltage, volts	—44				
Collector current, ma	—10				
Collector dissipation (at 27°C), mw	30				
Emitter current, ma	10	1.0	0.5 to 1.0	1.0	1.0
Ambient tempera-ture, °C *	70°C				
Collector resistance, megohms		2.0			
Base resistance, ohms		350			
Emitter resistance, ohms		25			
Base current amplifi-cation factor		22			
Cut-off current (approx), μa		6			
Noise factor (max), db †		25			
Input resistance, ohms ‡			1,400 to 800	0.35 meg	50
Load resistance, ohms			20,000	20,000	20,000
Power gain (matched input), db			37 to 39	13	32

* This is the maximum operating or storage temperature recommended.

† Measured under conditions for grounded-emitter operations at $V_{cb} = -2.5$ volts for a 1-cycle bandwidth at 1,000 cycles.

‡ Higher input impedances, without appreciable loss in gain, can be achieved by operating at lowered collector current.

terminal connections. A red dot identifies lead 1, the collector. Lead 2 is the base, and lead 3, the emitter. This numbering sequence has now become standard, although the red dot has been dispensed with in other transistors. For identification, lead 1 is set apart from the others, as shown under the Texas Instruments, Incorporated, characteristics. There are some variations in lead placement, particularly with power transistors. If any doubt exists, check the manufacturer's specifications.

Under the electrical data of the CK722, maximum values are listed first. The maximum collector voltage that can be safely applied is -22 volts. The maximum collector current that will prevent overheating of the collector is 10 ma. Collector dissipation, at 27°C, is 30 mw. Maximum emitter current recommended is 10 ma, and the highest recommended operating temperature is 70°C.

The next set of characteristics listed are the average characteristics at a temperature of 27°C. Note that temperature figures prominently in all transistor data because of the great effect that temperature changes have on transistor operation. It is most important that a transistor circuit be operated well within the maximum temperature specified for it.

The average collector voltage recommended is -6 volts, which is considerably below the -22 volts specified under the maximum data. Operating emitter current is suggested at 1.0 ma. The next three items list the internal resistances of the collector, base, and emitter electrodes, and this information is useful in circuit design (for which this data is principally intended).

The next item is the base-current-amplification factor, and its value is 22. This is obviously the β factor discussed above and is of interest for grounded-emitter applications. The value of α can be determined from this, since

$$\beta = \frac{\alpha}{1 - \alpha}$$

$$22 = \frac{\alpha}{1 - \alpha}$$

$$\alpha = \frac{22}{23} = 0.96$$

Cutoff current, listed under average characteristics, refers to the collector current which flows when the emitter current is zero. Its symbol is I_{co}, and it is important because it provides an indication of the lowest amount of heat that will be dissipated at the collector, from

which point the designer can adjust the circuit operating point so that the collector dissipation remains in bounds for all normal values of current and voltage. I_{co} is temperature-sensitive, and an increase in temperature will cause the value of I_{co} to rise. This, in turn, will raise the amount of heat dissipated at the collector and lead to another rise in temperature. Again I_{co} will rise, with the ascending temperature eventually resulting in transistor burnout. It is important, therefore, that whatever current is added to I_{co} under normal operating conditions does not cause the collector dissipation to exceed its safe limit.

The final item listed under average characteristics (for the CK722) is the maximum noise figure of this transistor. This value is high compared with a vacuum tube, but improvements being made in transistor manufacture give promise of much lower noise figures to come.

The remaining three general headings under electrical data provide the average operating values for use of the CK722 as a grounded-emitter, a grounded-collector, or a grounded-base amplifier. Note how the various values change for each, including the power gain when the input circuit resistance matches that of the input element of the transistor. As far as power gain is concerned, the grounded emitter is best, followed in turn by the grounded base and the grounded collector. The last figure is much lower than the first two, which is characteristic of this type of connection.

Figure 23a contains the characteristic curves of the CK722 for grounded-base and grounded-emitter operation.

The mechanical and electrical data for the Texas Instruments, Incorporated, type 200 transistor is given in Table 2. This is, for the most part, similar to the previous data. However, there are several additional items of information not previously given. For example, under average characteristics, we find collector capacitance (15 $\mu\mu$f) and frequency cutoff (0.9 Mc). The latter, it will be recalled, represents the frequency at which the gain is 0.707 of its low-frequency value. Here the manufacturer specifies a test frequency of 1,000 cps. Another frequency commonly used is 270 cps.

Typical operating values are specified for each of the three types of connections. Additional information in the form of power output and distortion is also specified for the grounded-emitter application.

The foregoing is representative of the information provided by the transistor manufacturer. Those designers who require additional data can usually get it by contacting the home office of the manufacturer or a local field office, if one is maintained.

Table 2. Tentative Specifications for Texas Instruments Type 200 NPN Junction Transistor

Mechanical Data

Case .... Metal, with insulating coating

Insulation .... Yellow; glass-to-metal seal between case and leads

Unit Weight .... 1 gram

Electrical Data

Recommended Maximum Ratings

Collector voltage	30 volts
Collector current	5 ma
Collector dissipation (at 25°C)	50 mw
Ambient temperature	50°C

Average Characteristics (at 25°C)

Collector voltage	5 volts
Emitter current	−1 ma
Collector resistance (minimum)	0.4 megohm
Base resistance	150 ohms
Emitter resistance	22 ohms
Current amplification factor * (minimum)	9
Collector cutoff current (maximum)	10 μa
Collector capacitance	15 $\mu\mu$f
Noise † ($V_c = 2.5$ volts, $I_e = -0.5$ ma)	26 db
Frequency cutoff † (α_c)	0.90 Mc
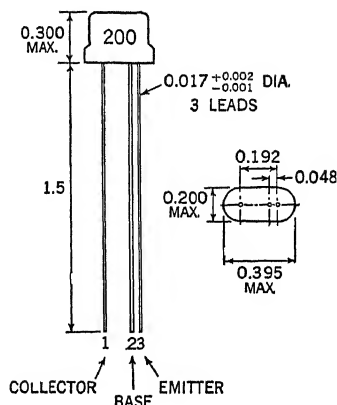
Typical Operating Characteristics ‡ (at 25°C)

	Grounded emitter	Grounded base	Grounded collector
Source impedance, ohms	500	60	15 k-ohms
Input impedance, ohms	480	35	9.5 k-ohms
Load impedance, ohms	20 k-ohms	0.1 meg	500
Power gain, db	37	30	12
Power output,§ mw	2.15		
Distortion, per cent	6		

* Emitter grounded.
† Noise and frequency cutoff are average, and individual units may vary.
‡ At test frequency of 1,000 cps and $V_c = 5$ volts, $I_e = 1$ ma.
§ With load impedance of 5,000 ohms and high source impedance.

FIG. 23a. The characteristic curves of the CK722 for grounded-base and grounded-emitter operation. (*Courtesy Raytheon Mfg. Co.*)

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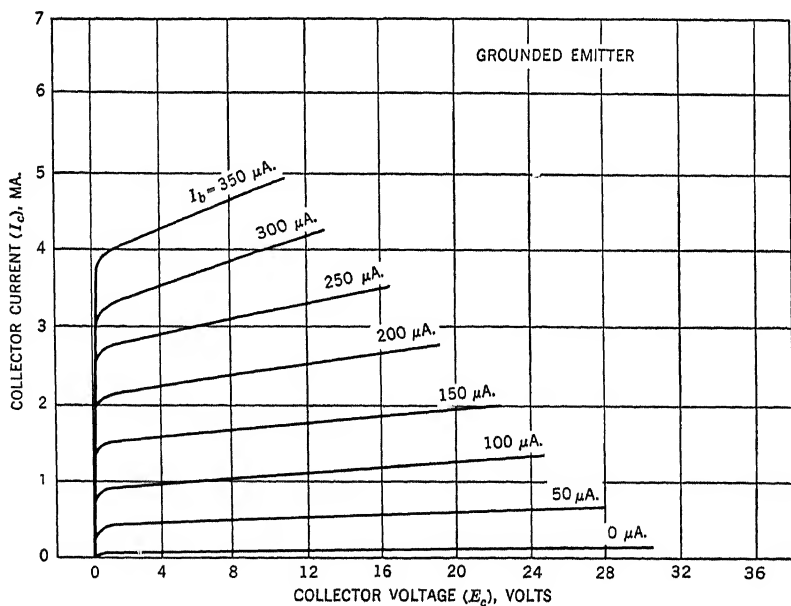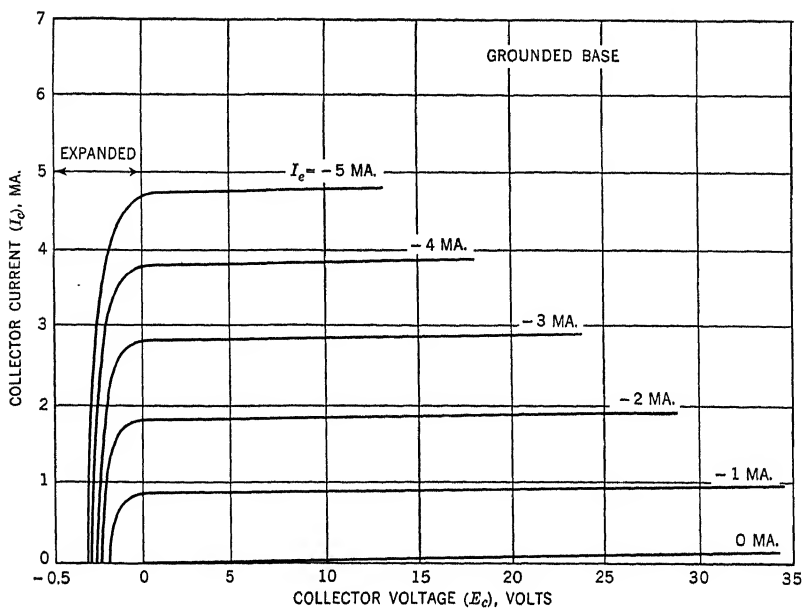
FIG. 23b. The characteristic curves of the type 200 junction transistor for grounded-base and grounded emitter operation. (*Courtesy Texas Instruments, Incorporated.*)
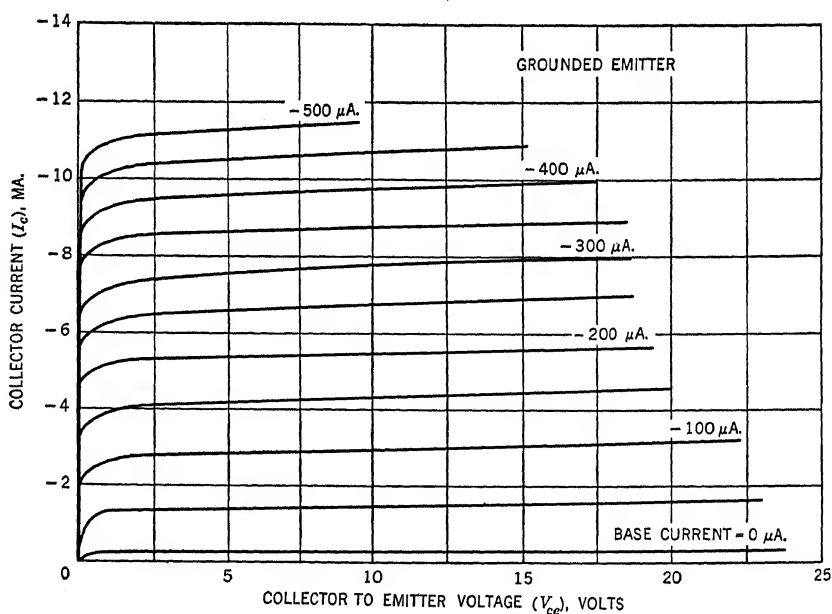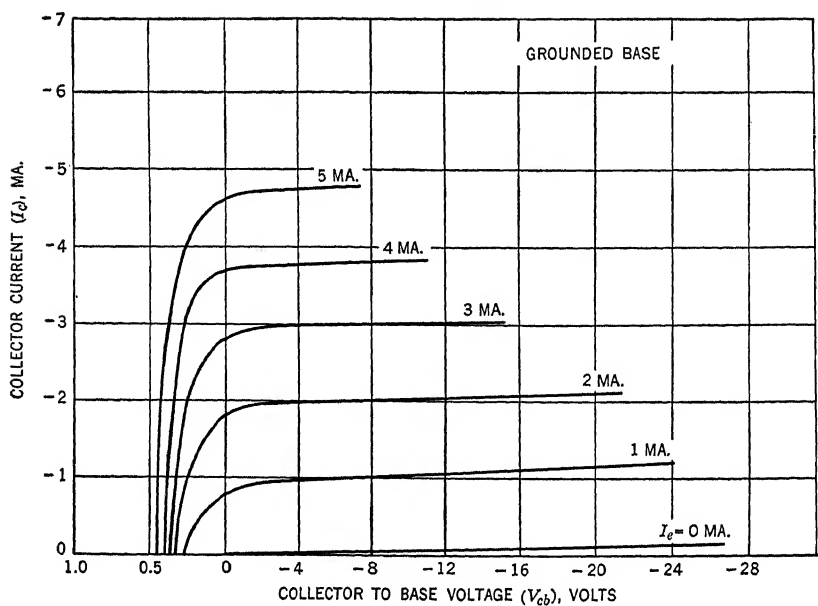
TRANSISTOR EQUIVALENT CIRCUITS

As one works with transistors, one finds that there is a considerable degree of dependence between the input and output circuits. This is in direct contrast to vacuum tubes, where the input and output circuits are relatively independent of each other. (Feedback effects which may occur can generally be counteracted by suitable means.)

In the grounded-emitter arrangement, for example, the variation in input resistance with load resistance is shown in Fig. 24. Note how the
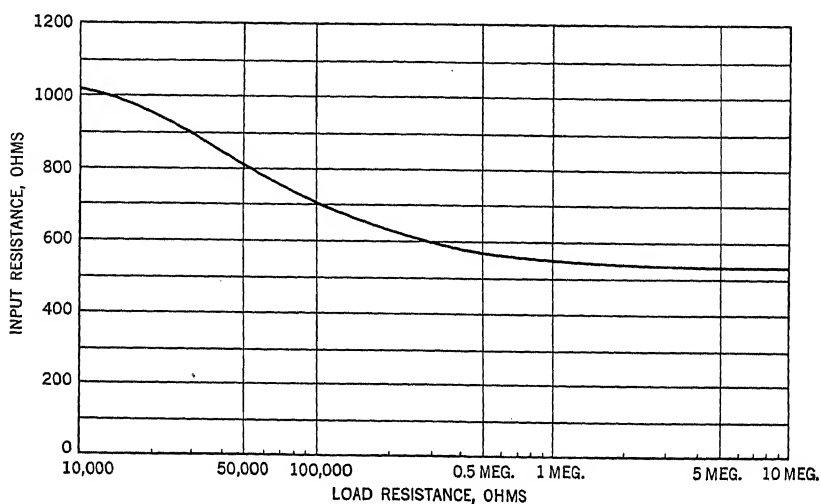
FIG. 24. The variation in input impedance as the load impedance varies in a junction transistor.

input resistance decreases with increase in load resistance, eventually leveling off to a value around 500 ohms when the load resistance becomes inordinately large. This is for a typical junction transistor. If a point-contact transistor is employed, the rather peculiar set of curves shown in Fig. 25 is obtained. Initially, when the load resistance is very small, the input resistance is slightly negative, on the order of 20 ohms or so. As the load-resistance value is raised, the input resistance becomes increasingly negative, reaching an infinite value for load resistances in the neighborhood of 20,000 ohms. Continued increase in load resistance causes the input resistance to go positive, starting from an exceedingly high value (theoretically infinite) and gradually decreasing until it levels off around 250 to 300 ohms when the load re-

sistance is so high that it could be considered infinite. Thus, for load values beyond 20,000 ohms, the point-contact transistor could be employed for normal amplification. For load values below 20,000 ohms, this transistor could be employed as an oscillator but not very well as an amplifier.
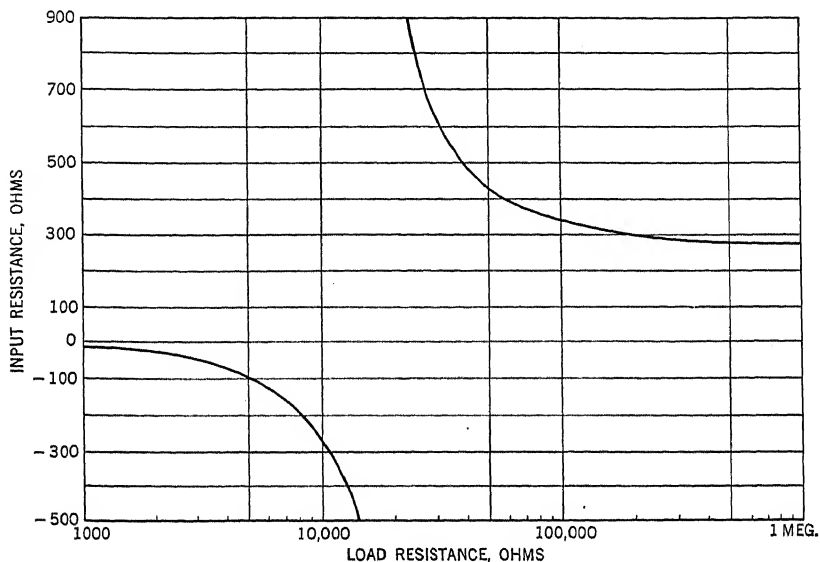
FIG. 25. The variation in input impedance for different load impedances in a typical point-contact transistor.

Similar curves could be drawn showing the effect on the output resistance for different input resistances. The reason for these interactions can perhaps be better understood when the equivalent electrical circuit of a transistor is examined. Equivalent circuits are convenient devices enabling an engineer to develop a relatively simple electrical network which will function in the same manner electrically as some complex circuit which he may be investigating. It is interesting to study the engineer's approach to equivalent circuits because it will give the reader a better appreciation of the value and purpose of these circuits.[*] The start is made with a little black box in which the circuit or system to be analyzed is contained. Access to the box is prohibited, and all we have from the box are four terminals, two representing the

[*] Patterned after A. Coblenz and H. L. Owens, "Transistors: Theory and Applications," pp. 90–93, McGraw-Hill Book Company, Inc., New York, 1955, and L. C. Peterson, Equivalent Circuits of Linear Active Four-terminal Networks, *Bell System Tech. J.*, October, 1948.

input and two the output. The procedure then is to take this black box and perform a series of four measurements on it. One measurement is to apply a signal to the input terminals 1 and 2 and record the voltage that is applied and the current that flows in the input circuit, with the output circuit open (see Fig. 26a). This will give us, when V_1 is divided by I_1, the input resistance R_1.

A second measurement is made by applying the signal to the input terminals of the black box and recording the current flowing in the input circuit and the voltage developed across the output circuit. This is illustrated in Fig. 26b. This measurement indicates what effect the input circuit has on the output circuit.
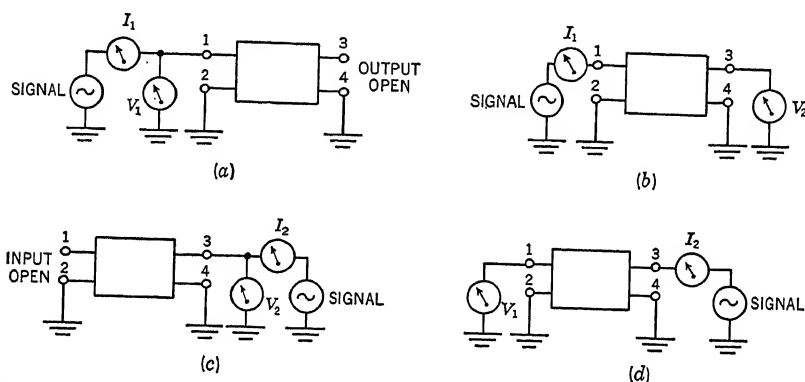
FIG. 26. These voltage and current measurements are made on a system in order to determine its equivalent circuit. (a) Signal is applied to input. Voltage and current measurements made on input, with output terminals open. (b) Signal is applied to input. Current flowing in input measured, together with voltage across output. (c) Signal is applied to output. Input open, voltage and current in output measured. (d) Signal is applied to output. Current flowing in output measured, together with voltage across input.

The third test is made with the signal generator connected across the output terminals and the voltage and current meters recording these respective quantities in the output circuit (see Fig. 26c). The input circuit is open.

The final check is made under the conditions indicated in Fig. 26d. Here we apply the signal to the output circuit and measure the voltage it produces across the input circuit.

The results of these four measurements are then used to draw a simple network which will give exactly the same results when the same measurements indicated above are made. If such a network can be found, then we know that it will act, under all conditions, as the circuit or system in the black box, and we can call this latter network

the equivalent of the box system and deal with it rather than the generally more complex system it replaces.

Using the foregoing method, the equivalent network obtained for a transistor is shown in Fig. 27a, where r_e is the internal resistance of the emitter, r_b the internal resistance of the base, and r_c the internal
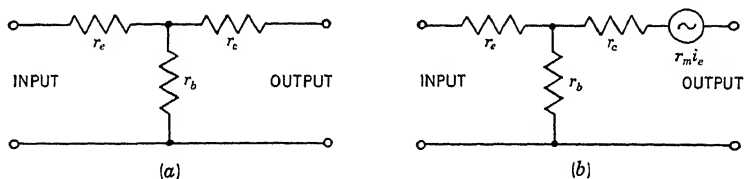
FIG. 27. Steps in the development of an equivalent circuit for a transistor. (a) Preliminary equivalent circuit of a transistor. (b) A more nearly complete equivalent circuit of a transistor.

resistance of the collector. Note that the base resistance is common to both the emitter and collector circuits, a fact that we discovered previously when studying the manner in which current was conducted through the transistor.

Now, if all we had in our equivalent circuit were these three resistances, then we would have a simple resistive network in which signals (or voltages) could pass from input to output or from output to input with equal ease. This, we know, is not true of transistors. Furthermore, a simple resistive network could introduce only attenuation, not amplification, and transistors do amplify. Obviously something more is needed, and that something is the small generator placed in series with r_c. For mathematical reasons which are related to the design equations of transistors, this generator is given a value of $r_m i_e$, where i_e is the current flowing through the emitter resistance r_e and r_m is a mutual resistance of this system. For our purpose here, we need simply regard this generator as adding its voltage to that of the input signal to produce a greater (i.e., an amplified) signal at the output. In this way we achieve an equivalent circuit which reveals how a signal applied to a transistor is amplified and just what that amplification will be under various types of load resistances.

For those readers who find this added generator strange or confusing, attention is directed to the equivalent circuit for a triode vacuum tube. This is shown in Fig. 28, and we note that a voltage e_1, applied between grid and cathode produces the same effect as a voltage in the plate circuit which is μ times greater. μ, of course, is the amplification factor of the tube.

Returning to Fig. 27, we begin to see why the input and output circuits of a transistor are so dependent on each other. Any current flowing in the collector circuit will also flow through r_b, and the voltage developed across here will directly influence the current flowing in the input circuit (containing R_g, r_e, and r_b). And, of course, anything that
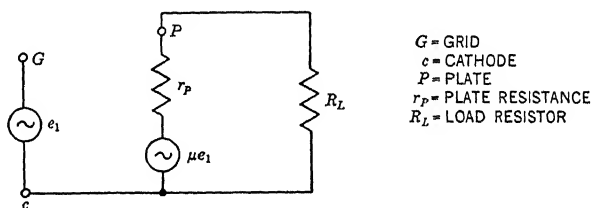
FIG. 28. The equivalent circuit of a vacuum tube. The incoming signal e_1 appears in the plate circuit as a greater voltage μe_1.

happens in the input circuit will be immediately felt in the output circuit. In a vacuum tube, where the grid is negative and the frequency is not very high, the equivalent circuit of Fig. 28 shows quite plainly that the grid and plate circuits are isolated from each other and we do not have the same dependence between the impedances in each circuit that we have in a transistor.

The equivalent circuit of a transistor is also useful in providing a physical picture of why point-contact transistors exhibit negative resistance while junction units do not. For convenience in following the ensuing discussion, the equivalent circuit is redrawn in Fig. 29.
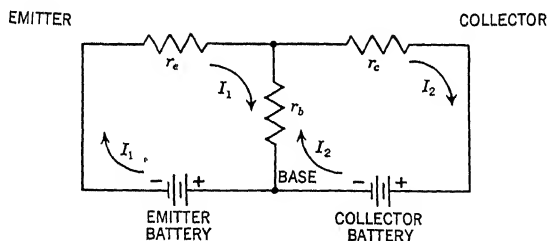
FIG. 29. The equivalent circuit of a point-contact transistor using P-type germanium. For the sake of simplicity, the generator $r_m i_e$ is not shown (see text).

If we assume a point-contact transistor with P-type germanium, then the d-c bias voltages for the emitter and collector will possess the polarities shown in Fig. 29. Electrons will flow in the emitter circuit in the direction indicated by the arrow labeled I_1 and in the collector circuit by the arrow labeled I_2. Note that both currents flow through

the base resistance in opposite directions, producing opposing voltage drops across r_b.

Now if the emitter voltage is raised, both I_1 and I_2 will increase. However, in point-contact transistors, the ratio of change in I_2 to change in I_1 falls between 2 and 3. This means that I_2 will rise faster than I_1 and, consequently, the voltage drop that I_2 produces across r_b will also rise faster than the voltage drop that I_1 produces here. At some point, there will be an over-all decrease in emitter-to-base voltage while the emitter current is rising. This produces a negative input resistance.

This same condition cannot occur in a junction transistor because the ratio of a change in collector current to a change in emitter current is *less* than 1 and the collector current cannot increase more rapidly than the emitter current. As a matter of fact, it falls progressively farther behind as the emitter current rises.

Since the negative resistance behavior of a point-contact transistor is related to the base resistance, decreasing this base resistance will aid transistor stability. One way to achieve this is to choose germanium which has a low resistivity, which means that it contains a greater amount of impurity. Another method, careful surface processing of the germanium crystals, frequently will reduce surface leakage between the emitter and collector contacts, thus reducing the value of equivalent base resistance. In still another approach, it has been discovered that as the spacing between the point contacts are increased, the base resistance decreases. Remember, however, that as the point-contact spacing increases, the frequency response decreases (see Fig. 6). The latter behavior, of course, is related to the time it takes electrons or holes to travel from emitter to collector. Thus, a compromise is necessary, with most emphasis on the type of germanium used and the crystal surface.

In transistor oscillators, a negative resistance is desired, and so it is possible to convert a stable point-contact transistor into one which is unstable (i.e., possesses a negative input resistance) by simply adding resistance to the base circuit. This is actually done in several of the oscillators discussed in Chap. 5.

QUESTIONS

1. Explain why junction transistors are capable of handling greater amounts of power than point-contact transistors.

2. How does the noise figure of transistors compare with the noise figure of vacuum tubes? How does the noise figure of transistors vary with frequency?

3. List some of the factors which govern the frequency response of transistors.

4. Why does an NPN transistor possess a higher frequency response than a comparable PNP transistor?

5. How can the frequency response of a point-contact transistor be improved? A junction transistor?

6. Describe the construction of the RCA alloy junction transistor.

7. How does this design help improve frequency response?

8. How does the surface-barrier transistor operate?

9. Define the cutoff frequency of a transistor.

10. Why must the collector-dissipation rating of a transistor be reduced when the unit is employed beyond a certain temperature?

11. Name some of the ways in which the collector-dissipation rating can be increased.

12. How are PNP and NPN transistors differentiated schematically? What other conventions are employed in drawing transistor symbols?

13. Compare the elements in a triode vacuum tube with the sections of an NPN transistor. Do the same with respect to the d-c voltages which each device receives.

14. Draw the circuit of a grounded-base transistor amplifier, complete with d-c biasing voltages and input and output terminals. Draw the vacuum-tube counterpart of this circuit.

15. Follow the same procedure as in Question 14 for a grounded-emitter transistor amplifier. Draw the vacuum-tube counterpart of this circuit.

16. Do the same for a grounded-collector transistor amplifier.

17. Which of the three types of amplifier is best suited for a high-input-impedance, low-output-impedance application? Which arrangement provides the best voltage and power gains? Would the same results be obtained if vacuum-tube amplifiers were employed? Explain.

18. Differentiate between the α and β values of a transistor.

19. Describe how the β value of a transistor may be determined from its characteristic curves. For your illustration, use Fig. 22.

20. What does the notation I_{co} stand for, and why is it important enough to be listed in the characteristic data chart of a transistor?

21. How can you identify the various element leads of a transistor? Indicate two widely used methods.

22. What characteristics are generally given for a transistor in the manufacturer's listings?

23. Why is there greater dependence between the input and output circuits of a transistor than of a vacuum tube?

24. Draw the equivalent circuit of a transistor.

25. Why do point-contact transistors exhibit negative resistance, while junction transistors do not?

CHAPTER 4

TRANSISTOR AMPLIFIERS

Introduction. In preceding chapters we noted how a transistor functions internally and how it achieves the desired goal of amplification. Several simple amplifier circuits were touched on in the course of this discussion; these, however, were incidental to the main discussion of transistor characteristics. In the present chapter we shall turn our attention completely to transistor amplifiers to see what forms they take and how they operate.

Transistors, like tubes, can be employed in three different configurations. These are designated as grounded, or common, base; grounded, or common, emitter; and grounded, or common, collector. By way of review, it will be recalled that the common-base arrangement provided less than unity current gain, a very low input impedance, a high output impedance, and no phase reversal of the amplified signal. In the common-emitter amplifier, the current gain β was quite large, the input impedance was relatively low, the output impedance was moderate, and the signal suffered a phase reversal in going from input to output. In the final configuration, the common collector, the input impedance was high, the output impedance was low, and there was no signal phase reversal. The last arrangement was the direct counterpart of the vacuum-tube cathode follower.

COMMON-BASE AMPLIFIER

Practical circuits employing each of these three transistor amplifier arrangements are shown in Figs. 1, 2, and 3. In the first illustration (Fig. 1) a Raytheon CK722 transistor is used.* If we did not know offhand whether this was an NPN or a PNP transistor, we could use the emitter and collector battery polarities as our clue. The emitter

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* *Aerovox Research Worker,* April-May, 1953.

must be biased in the forward direction. This means that the positive terminal of B_1 must drive the common-emitter carriers to the emitter-base junction. A positive field, such as produced by the positive battery terminal, will repel holes. Therefore, we know that the emitter section is formed of P-type germanium. It follows then that the base has N-type germanium and the collector, P-type germanium. In short, the CK722 is a PNP transistor.
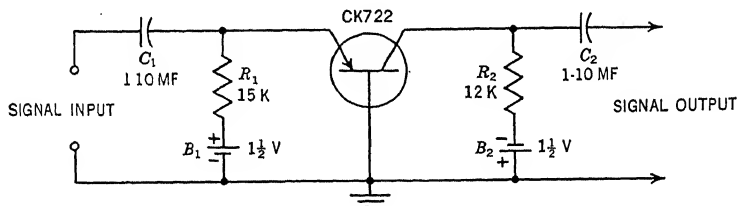
FIG. 1. A common-base transistor amplifier.

Now to the circuit of Fig. 1. The input signal is RC-coupled to the emitter. The emitter bias is established by battery B_1, 1.5 volts. Current flow through the emitter is governed by R_1, a 15,000-ohm resistor. By using Ohm's law,

$$E = IR$$
$$1.5 = I \times 15,000$$

we find that

$$I = 0.10 \text{ ma}$$

Actually, by this reasoning we completely neglected the resistance of the emitter-base section. However, the latter is so small, with the indicated battery arrangement, that it scarcely alters the total current flow. Actually the emitter-base potential is on the order of 0.1 volt or possibly less.

The output, or collector, circuit possesses a 1.5-volt battery and a 12,000-ohm load resistor. Signal voltages developed across R_2 are then capacitively coupled to the next stage or output device.

The two coupling capacitors C_1 and C_2 are shown with capacitance ranges from 1 to 10μf. The use of such high values is dictated by the relatively low input impedance of this stage (and for C_2, the relatively low input impedance of the following stage). With an input impedance on the order of 1,000 ohms, it is desirable that the impedance offered by C_1 to the lowest operating frequency be no more than 100 ohms. To achieve this, large values of capacitance must be used. Fortunately, the working voltage requirements are extremely low (here on the order

of a volt or two), so that high-valued electrolytic capacitors can be manufactured at reasonable cost and with considerable compactness.

It is, of course, desirable to make C_1 (and C_2) as large as possible. When 1-μf values are used, the frequency response is such that the gain at 100 cycles is 25 per cent of the gain at 1,000 cycles. When we change to 10 μf, the 20-cycle gain rises to 67 per cent of the 1,000-cycle value, thus showing a marked improvement. The extent of the high-frequency end of the curve is governed by the capacitances shunting the circuit and the manner in which α drops off with frequency.

Two batteries are required for this circuit. Drain on B_1 is 150 μa; on B_2 it is 100 μa. The use of two batteries is somewhat of a disadvantage, which can be remedied by inserting a resistor in the base lead, as shown in Fig. 2. Current flowing through this resistor, in the direction shown
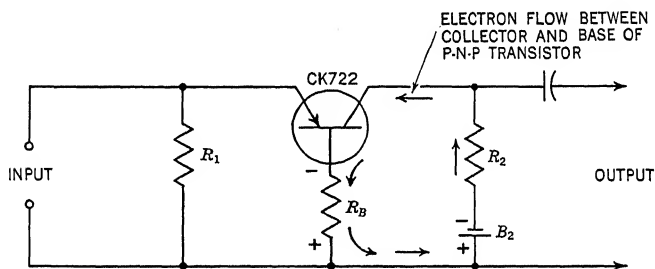
Fig. 2. The necessary biasing voltage between emitter and base can be achieved by inserting a resistor (such as R_B) in the base lead.

for a PNP transistor, will develop a voltage with the polarity indicated. The path between emitter and base may be completed through the input terminals (as, for example, the secondary of a transformer or a resistor such as R_1 may be used). In either event, the voltage developed across the base resistor will be applied between emitter and base and provide the necessary biasing voltage.

It will be appreciated that this base resistor, if left unbypassed, will introduce degeneration, reducing the over-all gain of the stage. In this sense it is equivalent to the cathode resistor of a vacuum-tube amplifier, although the base of a transistor is not the counterpart of the vacuum-tube cathode.

COMMON-EMITTER AMPLIFIER

Much more widespread than the use of common-base transistor amplifiers are common-emitter amplifiers. With this arrangement we

obtain greater voltage and power gain. A circuit using the CK722 in a common-emitter arrangement is shown in Fig. 3.* Connection of the input and output resistors and capacitors remains the same as in the previous amplifier. Note, however, the use of a single battery for both circuits. This is possible because the emitter is common to both input and output circuits and both collector and base possess the same relative polarity with respect to the emitter.
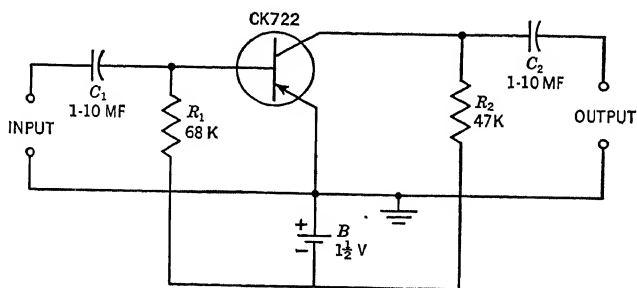
FIG. 3. A single-stage grounded-emitter. A CK722 or any similar PNP transistor may be used.

With the component values given in Fig. 3, voltage gain of this stage is between 40 and 50 when B is 1½ volts and 80 to 100 when B is 3 volts.

A form of common-emitter amplifier that is frequently seen is shown in Fig. 4. The chief difference between this circuit and that of Fig. 3 is
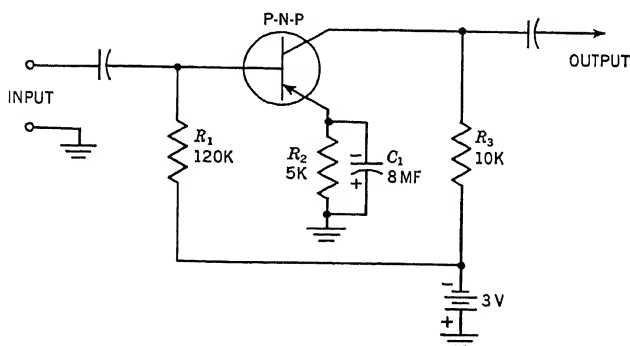
FIG. 4. A common-emitter amplifier that employs a stabilizing resistor R_2.

the 5,000-ohm resistor R_2 and filter bypass capacitor C_1 which have been inserted in the emitter lead. Resistor R_2 serves to stabilize the

* *Aerovox Research Worker*, April-May, 1953.

circuit by compensating for differences between transistors and by reducing the effects caused by temperature drift. Capacitor C_1 is shunted across R_2 to prevent degeneration with its reduction in gain. In some instances, the added stability provided by degeneration may be desired, in which case C_1 would be omitted.

This problem of amplifier stability being affected by temperature changes is more serious in common-emitter and common-collector circuits than it is in common-base circuits because of the presence of a cutoff current I_{co}, which was mentioned briefly in Chap. 3. I_{co} is the current that flows through the collector-base sections when the emitter current is zero. It stems from the presence of minority carriers in the base and collector sections, and it gives rise to a small current when the collector is reverse biased. I_{co} is generally below 10 μa, and it is independent of the emitter current. Its value is determined chiefly by the particular transistor being used and by the temperature. It is the latter dependence which is particularly significant.

When a transistor is connected with the base common to both input and output circuits, as in Fig. 1, then the total collector current that flows is made up of two components; these are

$$I_c = \alpha I_e + I_{co}$$

That is, I_c, in a junction transistor, is equal to 95 per cent (or so) of the emitter current I_e plus the collector cutoff current I_{co}. Since I_{co} is in microamperes and I_c is at least several milliamperes and frequently much higher, changes in I_{co}, unless they are drastic, will not seriously increase the heat dissipated at the collector. Hence, we need not take other than the normal precautions with common-base amplifiers.

Consider, now, the common-emitter circuit (Fig. 3). I_{co} still flows between the base and collector sections, but now the base current *determines* the amount of collector current flowing. This, too, we noted in Chap. 3, and it was because of this relationship that we developed a second current-gain factor β, which is equal to

$$\frac{\alpha}{1 - \alpha}$$

and values of β of 30 or more are not unusual. The total collector current now flowing is given by

$$I_c = \beta I_b + (1 + \beta) I_{co}$$

Previously, the factor $(1 + \beta) I_{co}$ was ignored. However, when the transistor is subjected to fairly wide ranges in temperature, it is possible for this factor to develop values high enough to affect transistor

operation seriously. I_{co} is extremely sensitive to temperature, and any increase in this current will be magnified 30 or more times because of the presence of $(1 + \beta)$. This can have a marked effect on the total collector current. The latter, in turn, causes the collector dissipation to rise, which raises the operating temperature and with it I_{co}. Again the increase in I_{co} is magnified 30 times, with the collector current build-up continuing until it exceeds the safe operating limit and the transistor is destroyed.

The insertion of a series resistor in the emitter leg is designed to prevent the foregoing action from occurring. If we use the circuit of Fig. 4 as an illustration, 95 per cent of the collector current will flow through the emitter resistor. The voltage drop produced across R_2 serves to make the emitter negative with respect to ground. Note, however, that the base is also negative with respect to ground, and hence the base-emitter voltage will be the difference between the battery voltage drop across R_1 and the smaller voltage drop across R_2. Now let us say that the collector current rises because of a temperature-induced rise in I_{co}. This will cause the voltage drop across R_2 to increase, making the over-all base-to-emitter voltage less negative than it was before. This is actually working against the forward biasing voltage of the base-emitter circuit, resulting in *less* emitter current. Hence, we are counteracting the rise in I_c by decreasing I_b and I_e. In this way we achieve stabilization of our amplifier circuit.

A variation of this stabilization circuit is that shown in Fig. 5. Here the base is connected to a voltage divider. This arrangement provides
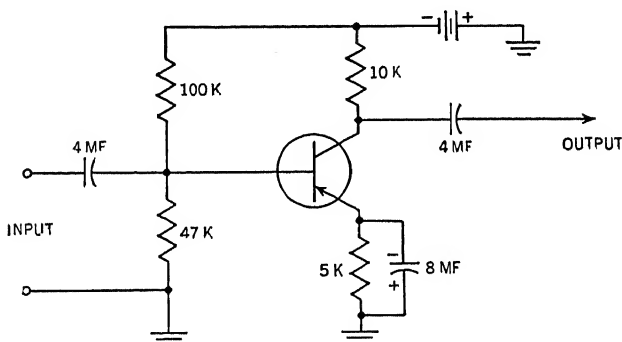

FIG. 5. A variation of the stabilized amplifier of Fig. 4.

greater stabilization than its predecessor, but the additional resistor does absorb more power from the battery. In this sense, then, this circuit is less efficient.

COMMON-COLLECTOR AMPLIFIER

A single-stage common-collector amplifier is shown in Fig. 6. The input signal is applied between base and ground. However, since the collector is at a-c ground potential, owing to C_1, we can say that the signal is effectively being applied between base and collector. The
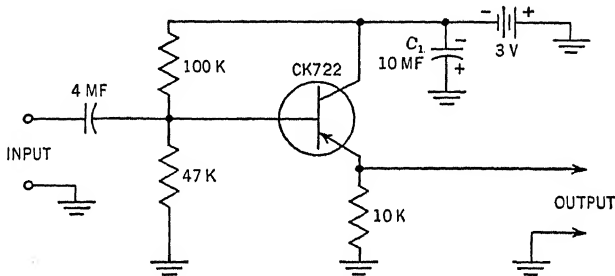
FIG. 6. A single-stage common-collector amplifier.

output is taken from a load resistor between emitter and ground or, what is the same thing, between emitter and collector. This circuit has a high input impedance, on the order of 50,000 ohms or more, and an output impedance of less than 100 ohms. The voltage gain of a common-collector amplifier cannot exceed 1, and in the circuit shown it is about 0.3. Power gain, however, is 15. The voltage gain is relatively independent of frequency, but the current gain falls off with frequency exactly the same as for a common-emitter amplifier. The power gain, therefore, falls off with frequency about midway between a common-base and a common-emitter amplifier.

Still another variation of the common collector is shown in Fig. 7a.* The load resistor is the 47,000-ohm resistor in the emitter leg. In addition, there is also feedback (furnished by C_2) between the emitter and base. The latter is designed to decrease the shunting effect of the base voltage divider.

The frequency response of this circuit for two different bias voltages is shown in Fig. 7b. Note that in neither case does this gain exceed 1. (The change in circuit presentation is purposely being made to help the reader become familiar with the different methods of illustration that he will encounter. The important items to look for are the point of application of the input signal and the take-off point of the output signal.)

* P. G. Sulzer, Junction Transistor Circuit Applications, *Electronics,* August, 1953.
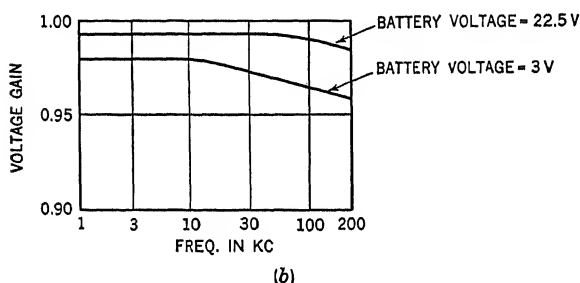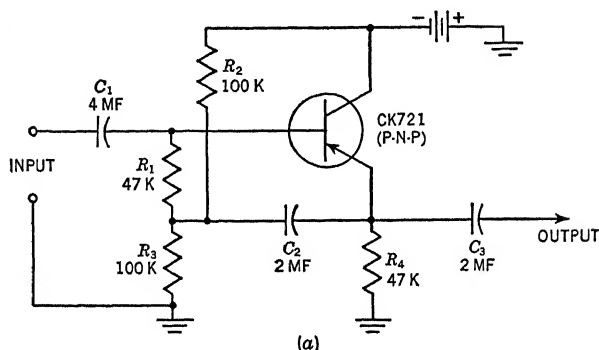
FIG. 7. (*a*) Another common-collector circuit. (*b*) The frequency response of the circuit shown in Fig. 7*a* for two different bias voltages.

CASCADED AMPLIFIERS

Transistor amplifiers, like vacuum-tube amplifiers, are seldom used singly. Rather, it is more common to find them in groups, with two, three, or more stages following each other in order, i.e., in cascade. When vacuum-tube amplifiers are used, it is a relatively simple matter to string them up, one after the other, because a conventional vacuum-tube amplifier has a much higher input impedance than output impedance. Hence, when we connect the input of one stage to the output of the preceding stage, we do not ordinarily affect the prior stage.

Consider, however, a transistor amplifier, say one designed with a common emitter. The input impedance is on the order of 1,000 ohms. The output impedance is more likely to be between 10,000 and 20,000 ohms. Obviously, a direct connection between two stages would result in a significant loss in gain due to the mismatch. If we accept this reduced gain, then it will be necessary to use more stages in order to obtain a desired amplification. Another solution would be to insert a

device (i.e., a step-down transformer) which will match the higher output impedance of one stage to the lower input impedance of the following stage. This solution has been used, and special miniature transformers (Fig. 8) have been devised for this purpose. Trans-
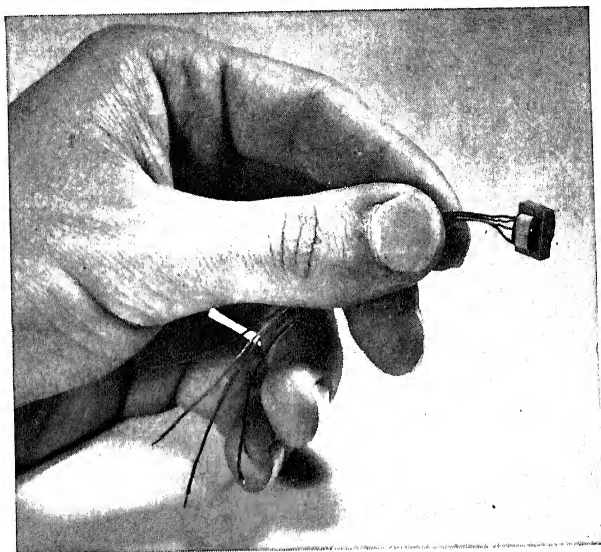
FIG. 8. A special miniature transformer designed for transistor application.

formers, however, do not ordinarily possess the same flat frequency response that can be obtained from RC networks. Also, transformers are more costly, and hence it is often more desirable, from an economic standpoint, to add an extra amplifier stage and use RC coupling than to revert to transformer coupling. However, both methods are used, and typical amplifiers of both types will be examined.

A two-stage transformer-coupled, grounded-emitter amplifier is shown in Fig. 9.* The interstage transformers have primary impedances of 20,000 ohms each and secondary impedances of 1,000 ohms each. Capacitators C_1 and C_2 are 10 μf in value, and resistors R_1 and R_2 both are 150,000 ohms. The two resistors are needed to establish the proper forward bias for the base-emitter circuits, and the two capacitors are inserted to prevent grounding of the base bias through the low d-c resistance of the transformer secondary windings.

Over-all power gain of this particular combination is approximately 50 db.

* See *Aerovox Research Worker*, April-May, 1953.

A resistance-coupled, grounded-emitter amplifier that will provide approximately the same amount of over-all power gain is shown in Fig. 10.* Note that three stages are required because of the mismatch between the output of one stage and the input of the following stage.
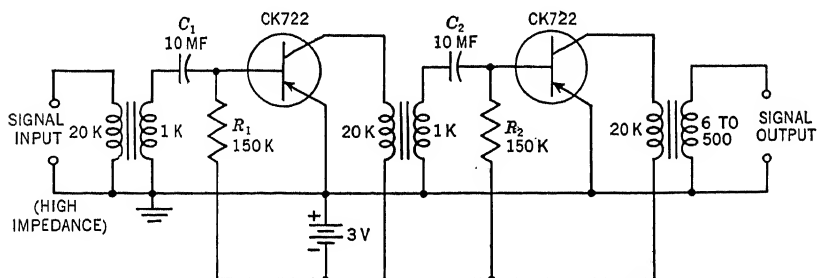
FIG. 9. A two-stage transformer-coupled grounded-emitter amplifier.

A two-stage amplifier with high input impedance and d-c stabilization is shown in Fig. 11.† The higher input impedance is achieved through the use of a grounded-collector stage. The signal it develops is then forwarded to a grounded-emitter amplifier. Insertion of 10,000-ohm resistors in the emitter leads of both transistors provides amplifier
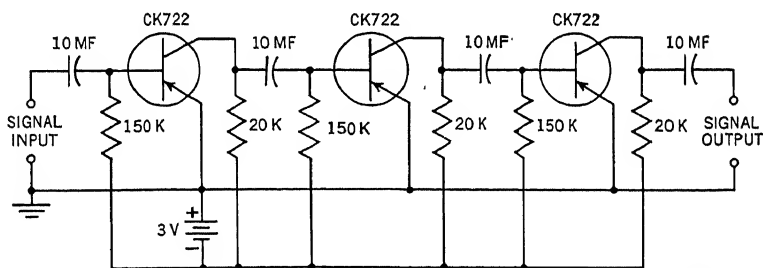
FIG. 10. A resistance-coupled grounded-emitter amplifier that will provide approximately the same amount of over-all power gain as the previous amplifier.

stabilization against temperature changes. The first 10,000-ohm resistor cannot, of course, be bypassed, since the signal is obtained from this point. In the second stage, however, an 8-μf bypassing capacitor is employed.

The frequency-response behavior of this two-stage amplifier, at two

* See *Aerovox Research Worker*, April-May, 1953.
† P. G. Sulzer, Junction Transistor Circuit Applications, *Electronics*, August, 1953.

different bias voltages, is shown in Fig. 12. In transistors, as in vacuum-tube circuits, we obtain more gain for higher voltages. The only precautions to observe are those dictated by the maximum safe operating currents and temperature.
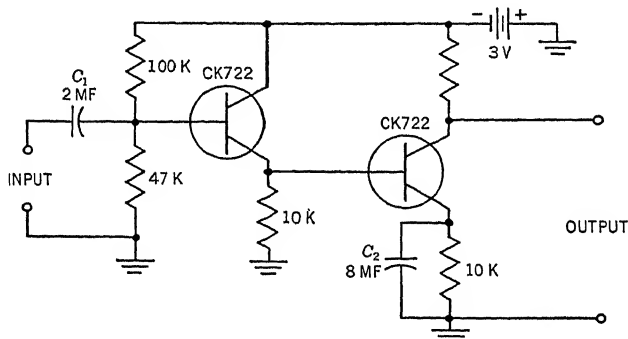
FIG. 11. A two-stage amplifier with high input impedance and d-c stabilization.

In cascaded amplifier circuits, it is frequently desirable to employ a decoupling filter across the battery or power supply. This is shown in Fig. 13, where R_f and C_f serve this function. The need for these components stems from the impedance of the power source (be it battery or an a-c supply) and the necessity of preventing positive feedback from a later stage where the signal level is high to a prior stage where it is low.

In choosing values for R_f and C_f, it is best to restrict R_f to fairly
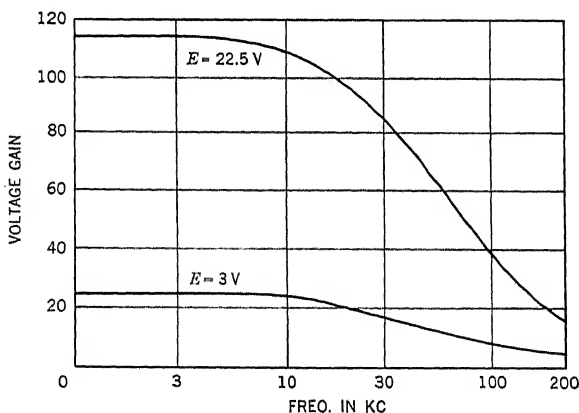
FIG. 12. The frequency-response behavior of the amplifier shown in Fig. 11 at two different bias voltages.

small values so that the operating voltage to the stages situated prior to R_f is not reduced to a value which will materially affect their gain. However, remember that the smaller R_f becomes, the larger C_f must be made in order to obtain effective filtering action. In general, the time
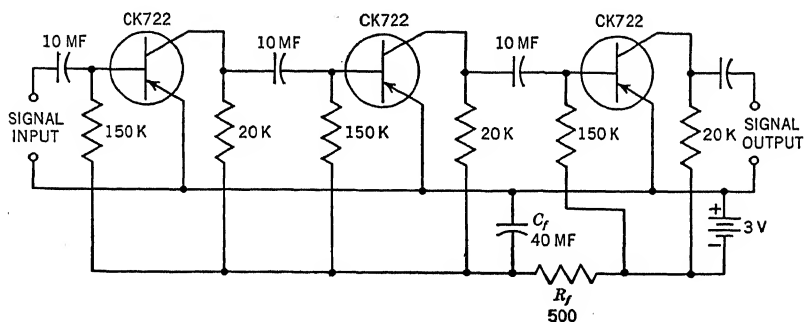
FIG. 13. A resistance-coupled amplifier with a decoupling filter C_f and R_f. It might be desirable to add additional filter sections if motorboating is encountered.

constant of $R_f \times C_f$ should be greater than $1/f$ for the lowest frequency passed by the amplifier. In computing this time constant, C_f is expressed in farads, R_f in ohms, and f in cycles per second. The values indicated for R_f and C_f are typical and will vary with the amplifier.

NEGATIVE FEEDBACK IN TRANSISTOR AMPLIFIERS

Negative feedback can be employed in transistor amplifiers for the same reason and in the same manner as in vacuum-tube amplifiers. Negative feedback will improve amplifier stability, reduce distortion, increase input impedances, and reduce the variations in gain that different transistors (or tubes) cause. The last feature is particularly important in transistor amplifiers because of the fairly wide range in characteristics that one encounters among transistors of the same type. Fortunately, this situation is being steadily improved, and one can depend upon a greater uniformity among transistors today than, say, two or three years ago. However, a wide latitude will still be found among similar units, and the use of negative feedback can often reduce the variations in amplifier performance caused by these differences to a considerable extent.

All the advantages of negative feedback are not obtained without some penalty, this being the loss in gain. However, the loss is not a serious one, because of the higher and higher voltage amplifications

which transistors are providing. We seldom lack sufficient gain; usually, we have more than we actually require.

A simple form of negative feedback is obtained by leaving the d-c stabilization resistor in the emitter lead unbypassed. This is a single-stage approach, to be used or not as desired by each of the various stages.

Another form of negative feedback is shown in the two-stage amplifier of Fig. 14.[*] The feedback loop here extends from the output
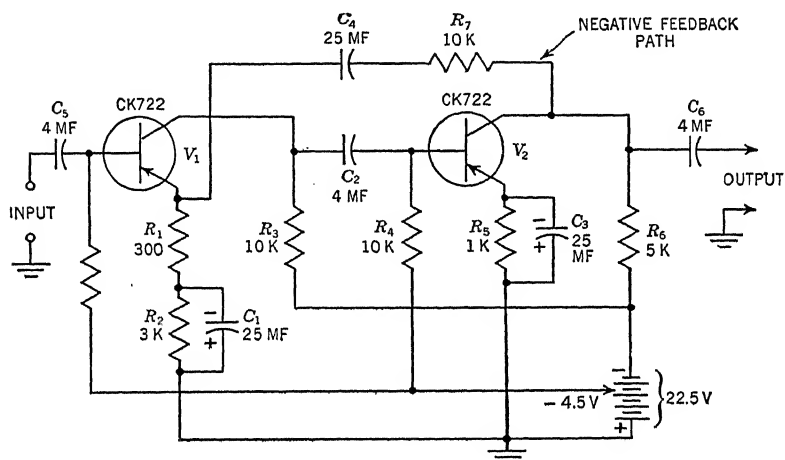
FIG. 14. A two-stage amplifier employing negative feedback.

circuit of V_2 to the emitter circuit of V_1. Involved in this feedback are two resistors R_1 and R_7 and one capacitor C_4. R_1 is needed to provide a means of inserting the feedback energy into the emitter circuit of V_1; hence, it was left unbypassed. R_2, in the same emitter circuit, is bypassed by C_1, and no feedback voltage is developed across these two parallel components. R_2, however, does provide d-c stabilization for V_1. R_5 does the same for V_2.

In the negative feedback of voltage, we know that the phase of the signal fed back must be 180° from the phase of the incoming signal. It may be instructive to check the signal polarities in the circuit of Fig. 14 to see if this condition holds true. (The procedure will also help the reader become familiar with the methods of checking signal polarities in transistor circuits.) If we assume that the incoming signal, applied to the base of V_1, is positive at some instant, then the signal voltage at the

[*] R. L. Riddle, Practical Two-stage Transistor Amplifiers, *Electronics*, April, 1954.

collector of this transistor is negative. This stems from the 180° phase reversal that occurs in a common-emitter amplifier. (If this action is hazy in the reader's mind, it is suggested that the material in Chap. 3 be reread.)

The negative signal at the collector of V_1 is also negative at the base of V_2. This produces a positive signal at the collector of V_2, and a portion of this signal is fed back to the emitter of V_1. Thus, we have a positive signal at the base and a smaller positive signal at the emitter. Since these two voltages will work in opposition to each other in forcing current through the emitter base, we obtain negative feedback.

The effect of negative feedback on the frequency response is shown in Fig. 15. Note how much flatter the curve is with the feedback. Also
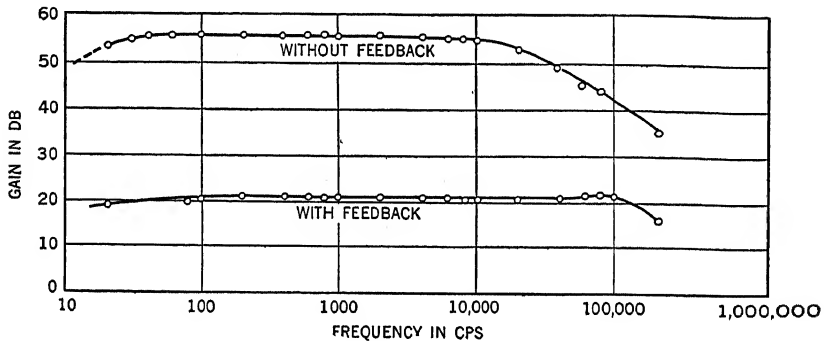
Fig. 15. The effect of negative feedback on the frequency response of the amplifier shown in Fig. 14. (*Courtesy Electronics.*)

instructive are the two curves in Fig. 16. The left-hand curve shows how the over-all gain will vary with different transistors when there is no feedback. Note how much better the action becomes when feedback is employed.
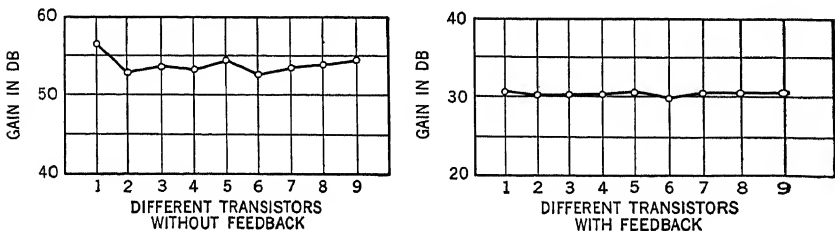
Fig. 16. Negative feedback in an amplifier (such as the one shown in Fig. 14) will serve to reduce the variations in over-all gain that different transistors will introduce owing to varying characteristics.

The point of feedback return is governed by the phase conditions in the circuit around which the feedback is sent. Consider, for example, the two-stage amplifier circuit shown in Fig. 17. The first stage is a grounded collector, and it does not introduce any phase reversal in the signal. The second stage is a grounded emitter, and it causes a
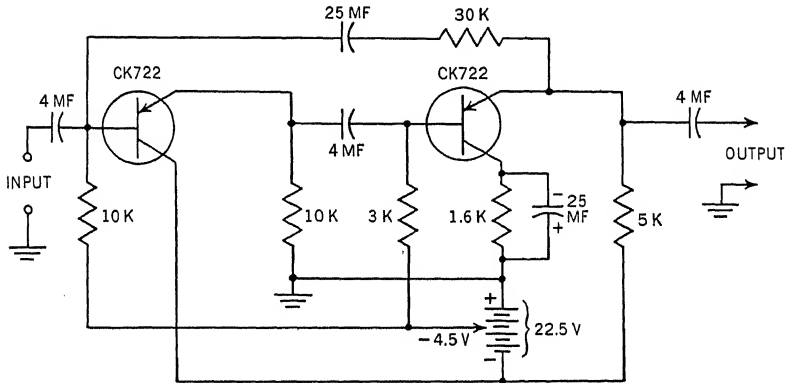
FIG. 17. Another negative feedback arrangement. (*Courtesy Electronics.*)

180° reversal. Under these conditions, the feedback line from the collector of the second stage can be brought back to any signal point prior to the base of this stage. The point chosen in this particular circuit is the base of the grounded-collector stage, but it could just as easily have been the emitter of this stage or the base of the second stage. At all these points, signal polarity is the same.

DIRECT-COUPLED AMPLIFIERS

We have spoken of and demonstrated *RC-* and transformer-coupled amplifiers. Another type of amplifier that is extensively used is the direct-coupled amplifier. In this circuit, a d-c path exists from the output of one stage to the input of the next stage. In its simplest form, a direct-coupled stage would appear as shown in Fig. 18. Here, the output device, a pair of headphones, is directly connected to the collector element of the amplifier stage. In order to employ the phones in this manner, their impedance should match the amplifier output, their operation should not be affected by the collector current flowing through them, and their d-c resistance should not be too high or the resulting voltage drop will reduce the collector voltage to too low a

value. In place of phones, we might use a relay, a meter, or any one of a number of devices.

Another d-c amplifier was illustrated in Fig. 11. Here, a direct path exists between the emitter of the grounded-collector stage and the base
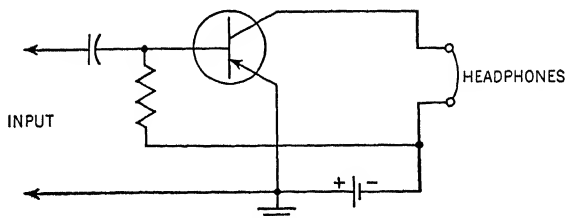
FIG. 18. A simple direct-coupled transistor amplifier.

of the following grounded emitter. Any decrease in low-frequency response in this circuit would be due entirely to the input capacitor C_1 and the second emitter bypass capacitor C_2.

Another type of direct-coupled transistor amplifier takes advantage of the fact that there are two basic kinds of junction transistors: NPN and PNP units. Each is the symmetrical counterpart of the other, and the polarity of an input signal necessary to increase conduction in a PNP transistor is the opposite of that necessary to increase conduction in an NPN transistor.
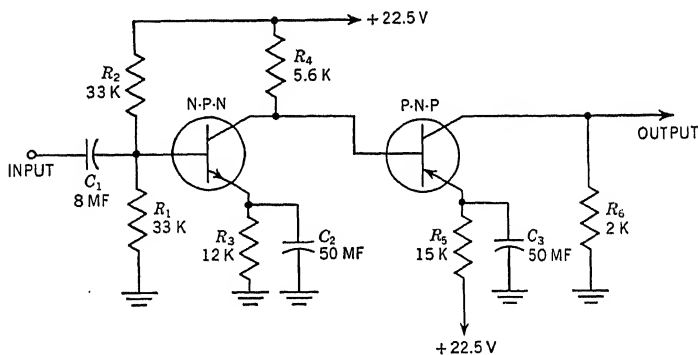
FIG. 19. A direct-coupled amplifier that makes use of the complementary symmetry of NPN and PNP transistors. Voltage gain of this system is 660; power gain is 53 db.

A direct-coupled amplifier that makes use of this symmetry is shown in Fig. 19.* The first transistor is an NPN unit; the second, a

* R. D. Lohmen, Complementary Symmetry Transistor Circuits, *Electronics*, September, 1953.

PNP type. The first stage is set up so that the collector current flowing through its load resistor R_4 develops just enough negative voltage here to make the base of the PNP transistor negative with respect to its emitter. This establishes the proper conditions in the emitter-base circuit of the PNP unit to bias it in the forward direction. Thus, by the proper choice of resistor values and battery potential, both stages will operate as class A amplifiers.

The application of a signal to the base of the NPN stage will result in an amplified signal appearing across R_6. For example, when the signal at the base of the NPN transistor goes positive, an amplified negative voltage will appear across R_4 (collector end negative with respect to battery end). This increasing negative voltage will provide an even greater forward bias for the base-emitter circuit of the PNP transistor, causing an increased flow of current through this unit. Electrons will flow up through R_6, making the top end positive with respect to the bottom end.

Thus, the positive signal applied to the input of this amplifier appears with the same polarity, but in amplified form, at the output.

Note the simplicity of this arrangement, requiring no coupling capacitors and only one battery supply. (Both 22½-volt potentials shown would come from one source.)

Another two-stage amplifier designed along somewhat similar lines is shown in Fig. 20. This system has for its sole purpose the amplifica-
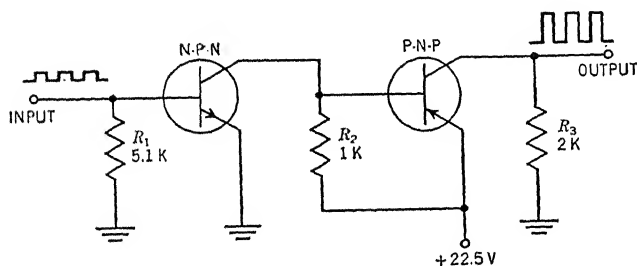
Fig. 20. A direct-coupled pulse amplifier.

tion of pulses, and as such, its mode of operation is modified accordingly. For example, if you examine the base-to-emitter circuits of both stages, you will note that no forward bias is employed. The characteristic curves for grounded-emitter operation (such as we have here) reveal that when the base current is zero (i.e., $I_b = 0$), the collector current is quite small. In terms of operation, this means that the

transistor is biased close to cutoff. This is true in both amplifiers of Fig. 20, although the second stage is not so close to cutoff as the first stage. This is because the small collector current that flows from the first transistor passes through R_2 and a small forward biasing voltage develops which shifts the operating point of the second transistor away from cutoff.

In the circuit of Fig. 20, a positive pulse of 0.25-volt input to the first stage is amplified to a 20-volt peak at the output of the second stage. Conduction is required only when the pulses are applied, hence the reason for the cutoff biasing.

POWER AMPLIFIERS

Just as we have voltage and power vacuum-tube amplifiers, so we have voltage and power transistor amplifiers. An important consideration in the design of a power transistor is the ability to handle safely the power which is dissipated at the collector. To help remove this heat,
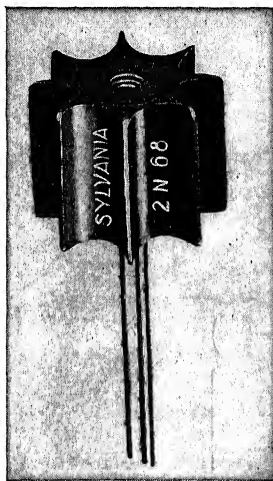
FIG. 21. A power resistor with radiating fins to help remove heat. (*Courtesy Sylvania Electric Products, Inc.*)
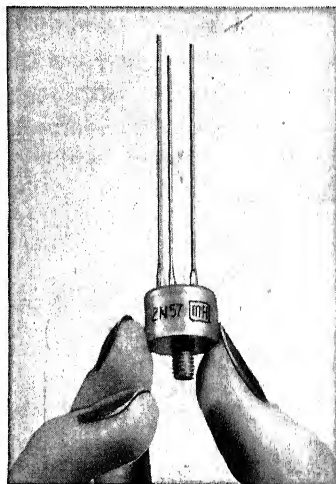
FIG. 22. A power transistor housed in a metallic container. The unit shown will provide a maximum power output of 6 watts when operated class A. (*Courtesy Minneapolis-Honeywell Regulator Co.*)

power transistors are built with radiating fins (Fig. 21) and in metal cases (Fig. 22). Internal heat is transferred to the external metal case by metallic conduction with very little drop in temperature. The metal

conducting surface may be soldered to any of the three transistor elements; in the power transistor of Fig. 22, the outer metal cup is soldered to the collector.

A cross-sectional view of this power transistor is shown in Fig. 23. Note how the collector (item 5) is set flush against an inner surface of the metal housing. If the design of the circuit permits, the transistor is mounted flush with the chassis, assuring the maximum dissipation of heat. In this case, items 7 and 11 of Fig. 23 would not be employed.
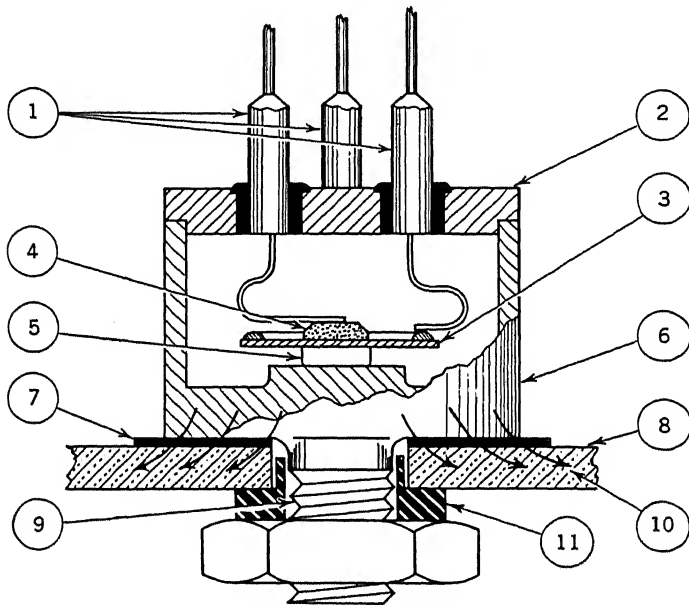
FIG. 23. A cross-sectional view of the power transistor shown in Fig. 22: (1) two-inch lead wires (base, collector, and emitter, respectively) for electrical connections; (2) metal top (with insulators for base and emitter leads), hermetically sealed for protection against contamination; (3) base (germanium crystal wafer with nickel reinforcing ring); (4) emitter (indium metal); (5) collector (indium metal); (6) metal case to provide durable enclosure for crystal assembly; (7) mica insulator to prevent power transistor from being grounded to chassis; (8) chassis (which usually serves as a heat sink); (9) mounting stud, integral part of metal case to provide solid attachment and facilitate good conduction for rapid heat dissipation to chassis; (10) arrows indicating path of direct heat flow; (11) plastic insulator bushing.

However, if the collector must be electrically insulated from the chassis, there would be a small mica washer (item 7) on one side of the chassis and a nylon bushing (item 11) to insulate the stud and nut from the other side of the chassis.

A series of four photographs illustrating how the size and construction of a transistor will change with power dissipation is shown in Fig. 24. The transistor in Fig. 24a is subminiature in size and is usable only where the voltage and current are quite small, as in the first few stages of a hearing aid. The transistor in Fig. 24b is standard, finding application in r-f and i-f amplifiers and in all low-power audio
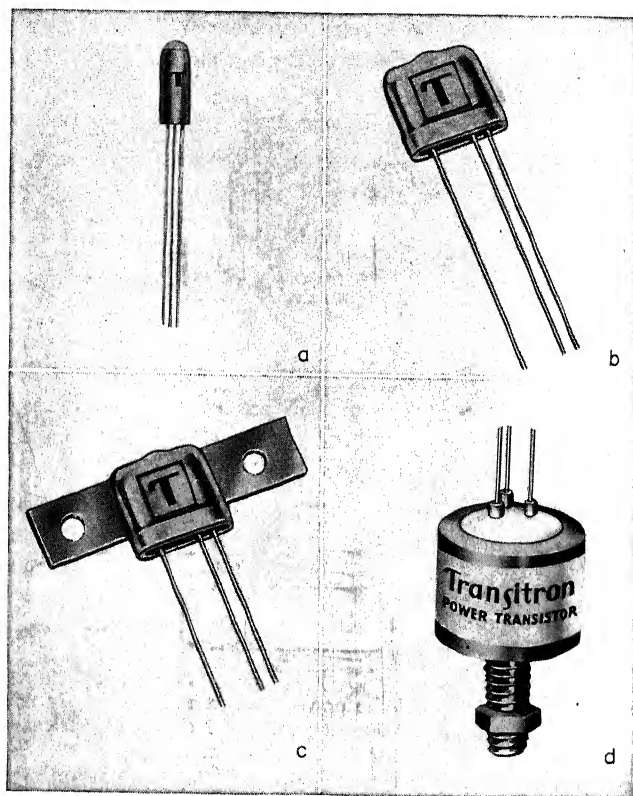
FIG. 24. A series of four transistors illustrating the variation in size and construction with power-dissipation requirements. (a) Subminiature. (b) Standard. (c) Medium. (d) Higher power. (*Courtesy Transitron Electronic Corporation.*)

stages. The transistor in Fig. 24c has a simple heat-dissipating mounting bracket, and it would be used in medium-power amplifiers where the heat to be dissipated is somewhat less than 1 watt. And finally, the transistor in Fig. 24d, labeled high power, would be used in applications requiring an output as high as 10 watts.

Power transistors have been developed with removable fin struc-

tures. This offers the advantage of fitting the fin structure to the particular application of the transistor. A small external structure would be employed for relatively low power outputs; a larger fin structure for higher power applications.

In another experimental power transistor, the unit is encased in a liquid-filled metal shell. Whatever heat is generated is transferred to the outer metal case by the liquid coolant. Previous mention has also been made of the fact that mounting a transistor against a metal surface enables it to get rid of its heat more efficiently. Hence, transistors so mounted will operate with greater power outputs than transistors which rely solely on the surrounding air to remove the heat. Forced-air cooling will also aid in heat dissipation, and this method is used in commercial and industrial equipment where the additional power obtainable is important.

While the stress has been placed on heat-dissipation methods, the reader will also recognize that changes will be required in the construction of the transistor elements themselves. These consist of changes in the resistivity of the germanium; modifications in the shape of the emitter, base, and collector elements; plus the development of different methods of forming the transistor. One type of suggested power transistor possesses the configuration shown in Fig. 25. The
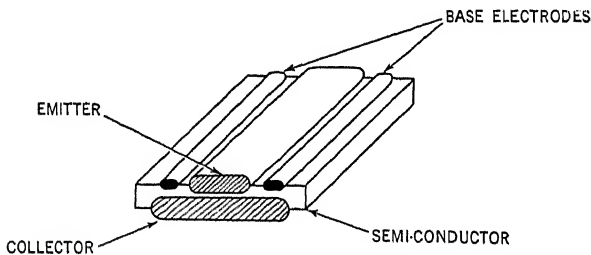
FIG. 25. The internal construction of one type of suggested power transistor. (*Courtesy Proc. IRE.*)

emitter is a long thin bar, flanked on either side by two long bars forming the base electrode. The collector, of course, is on the opposite side of the semiconductor. For medium-power applications where currents up to 2 amp are required, the transistor elements may be no longer than 1 cm.

For higher current requirements, the electrodes may be made longer or two or more of these transistor structures may be placed in parallel. If many bars are used, they may be connected together into a comb-like structure.

Class A Power Amplifiers. Circuit arrangements of single-ended power amplifiers do not differ to any marked degree from corresponding voltage amplifiers. Figure 26 illustrates two class A power amplifiers designed to drive the loudspeaker of an audio amplifier (or a radio or

(a)   (b)
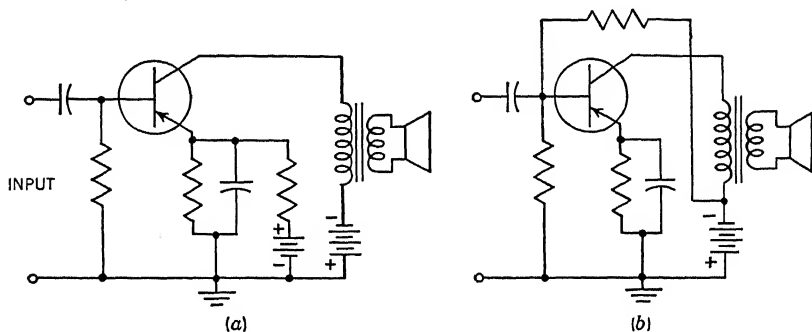
FIG. 26. Two class A power amplifiers.

television receiver). In one instance, two batteries are employed; in the other, a single battery. The output transformer would be designed to match the impedance of the collector on one hand and the loudspeaker on the other. The amount of power that may be obtained from this arrangement will be governed by the size of the battery and the permissible dissipation in the transistor itself.

As in vacuum-tube practice, a single-ended power amplifier can be operated only class A.

Power amplifiers can also be operated in push-pull. A typical illustration of an audio amplifier using a single driver stage and a class A push-pull output stage is shown in Fig. 27. All transistors are operated
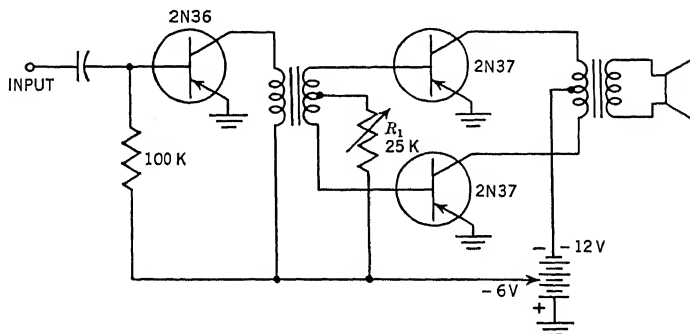
FIG. 27. An amplifier using a 2N36 driver and 2N37's in push-pull. All these transistors are PNP units.

with grounded emitters, and transformer coupling is employed between the driver and output stages and between the output amplifiers and the loudspeaker. The resistance R_1 is variable and is adjusted for a total collector current of 8 ma.

Push-pull amplifier operation results in the cancellation of second harmonics within the stage. For the same amount of distortion, then, a class A push-pull amplifier can be driven harder, providing greater output. It also means that we can obtain more than twice the output with push-pull operation than we can get using two similar transistors as single-ended amplifiers.

Class B Power Amplifiers. In class A push-pull operation, the average current that flows remains steady, whether or not a signal is being applied to the stage. More efficient operation can be achieved with class B operation, where each transistor is biased to cutoff. When no signal is applied, practically no current flows and no power is being dissipated.

The circuit of a class B push-pull amplifier is shown in Fig. 28. Three Sylvania type 2N68 power transistors are employed, the first one
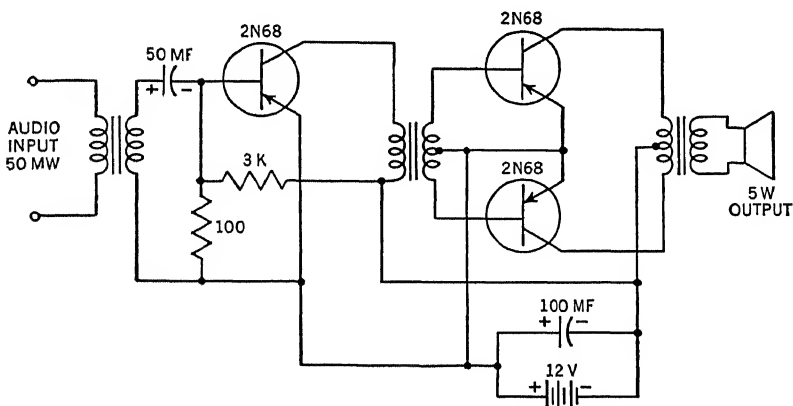
Fig. 28. A class A driver stage with a class B push-pull output. (*Courtesy Sylvania Electric Products, Inc.*)

as a class A driver amplifier, the remaining two in a class B output stage. With 50 mw of audio input power, up to 5 watts can be obtained at the speaker, using only a single 12-volt battery. Efficiency of the class B stage here is close to 75 per cent.

The reason for the high efficiency stems from the fact that with

zero signal, the total class B collector current is only 1 ma. For maximum signal, this current rises to 550 ma. In the preceding class A driver, the average current is 100 ma, signal or no signal.

Note that in the class B stage of Fig. 28, the emitter and base are connected together directly. This serves to reduce the collector current to the low value of 1 ma mentioned above. Actual collector current cutoff is seldom sought because of the nonlinearity of the transistor characteristic at low signal levels. For any given transistor, there is some value of base bias which results in a good balance between distortion and efficiency, and it is at this point that the stage is operated.

COMPLEMENTARY PUSH-PULL AMPLIFIERS

The complementary symmetry of PNP and NPN transistors was employed previously in direct-coupled amplifiers. These same features may also be utilized to obtain push-pull operation without any input or output transformers. This is possible because the collector currents of NPN and PNP transistors react in opposite ways when subjected to the same applied signal.

To see this more explicitly, consider the class A push-pull amplifier
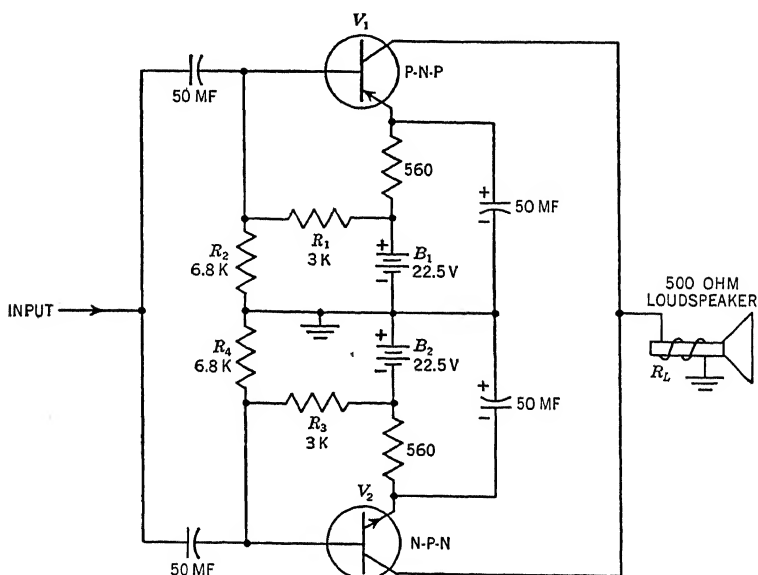
FIG. 29. A push-pull class A amplifier using neither input nor output transformers.

shown in Fig. 29.* At the top of the illustration we have a PNP transistor; below, an NPN unit. Both are suitably biased with a 22.5-volt battery (one for each transistor). R_1 and R_2 for the PNP transistor and R_3 and R_4 for the NPN transistor serve to establish the base-to-emitter bias suitable for class A operation. The 560-ohm emitter resistors provide d-c stabilization. Each of these resistors is suitably bypassed to prevent a-c degeneration, which would reduce the gain of this amplifier. The load is a 500-ohm voice coil of a loudspeaker, and it is directly connected to the collectors of the two transistors. A single input line is provided, with the base of each transistor connected to this line.

Assume, now, that a sine wave is being amplified and, at the moment in question, the positive half of the sine wave is active. This means that both bases will be driven positive simultaneously. In V_1, this will cause the base-emitter current to decrease and, with this, the collector current. Since the collector current flows up through R_L (i.e., the speaker voice coil), it will serve to make the top, or collector, end of this load impedance less positive or more negative.

Now let us turn to the NPN transistor. The path for its output current is from the collector to R_L. Hence the voltage drop across R_L due to this transistor is such as to make the top end of R_L negative.

When the positive half of the applied signal reaches the base of the NPN transistor, it acts to increase the forward bias here, increasing the base-emitter current. This, in turn, increases the collector current, causing more of a voltage drop across R_L, raising the negative potential present at the top of the load. This serves to work with or strengthen the voltage drop produced by the PNP transistor.

During the next half cycle, when the negative half of the signal is active, the reverse set of conditions occurs. That is, the current through the PNP transistor increases, producing more of a positive voltage across R_L. At the same time, the current through the NPN transistor decreases, lowering its negative voltage drop across R_L, which, in essence, is equivalent to a positive increase.

Thus, both sections of this circuit work in conjunction with each other, producing a larger output than either one could by itself. This is demonstrated in Fig. 30, where the individual output waveforms of each transistor are shown, together with the combined waveform. Note the differences in relative sizes.

A class B push-pull transistor amplifier with complementary sym-

* R. D. Lohmen, Complementary Symmetry Transistor Circuits, *Electronics,* September, 1953.

WAVEFORM WITH THE N-P-N UNIT ONLY

WAVEFORM WITH THE P-N-P UNIT ONLY

WAVEFORM WITH BOTH UNITS
IN THE CIRCUIT
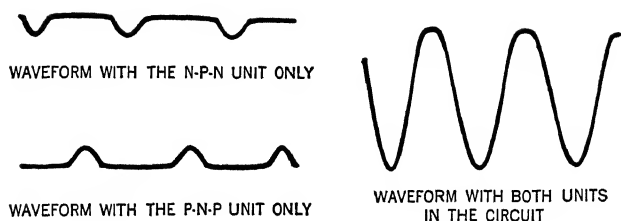
FIG. 30. Waveforms in the push-pull amplifier of Fig. 29.

metry that can feed its output directly to the 16-ohm voice coil of a loudspeaker is shown in Fig. 31. Across the top section of the diagram we have a PNP transistor directly coupled to an NPN transistor. Across the bottom section we have the reverse situation. Both halves are similar to the direct-coupled amplifier of Fig. 19 and operate in the same manner. In addition, the two sections form a push-pull arrangement. Power gains on the order of 30 db (i.e., 1,000 to 1 ratio) have been obtained in this manner.
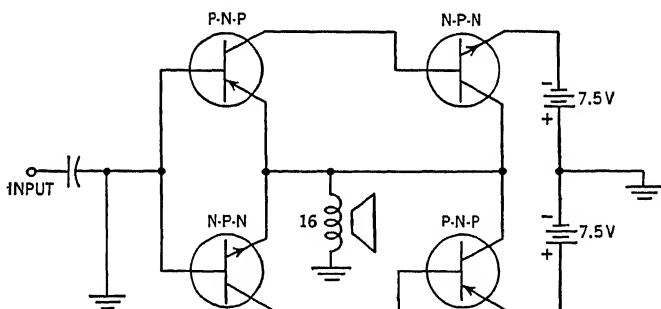
FIG. 31. Another push-pull amplifier using complementary symmetry. (*Courtesy Pros. IRE.*)

PHASE-INVERTER CIRCUITS

Oppositely phased signals of closely similar amplitudes can be obtained from a single transistor stage as shown in Fig. 32. One output voltage is taken from across the emitter resistor, while the second output voltage (of opposite phase) is obtained from the collector load resistor. While perfect balance cannot be obtained, because the current gain α is not equal to 1, still the voltages can be made to approach each other quite closely. Typical values of voltage gain to both outputs are shown in the diagram.
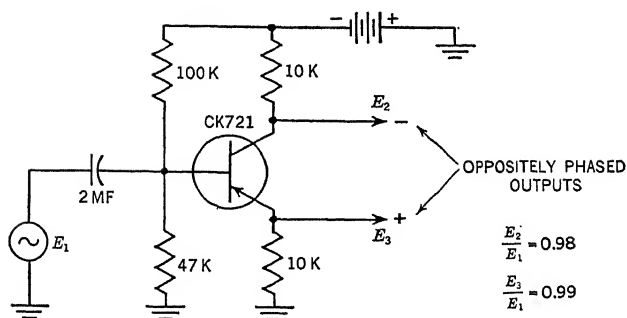
FIG. 32. A transistor phase inverter. (*Courtesy Electronics.*)

In a vacuum tube, the grid does not ordinarily draw any current. Hence, whatever current passes through the plate circuit also flows entirely through the cathode resistor (see Fig. 33). By having equal-valued resistors in the plate and cathode legs of the tube, equal output voltages will be obtained. In the transistor circuit (Fig. 32) a portion of the emitter current does not reach the collector. Hence, equal-valued collector and emitter resistors will not produce equal output voltages. If we alter the resistances to achieve better balance, we change the circuit operating conditions, including the various currents that flow. Thus, while we may come close, we shall not attain a perfect balance.
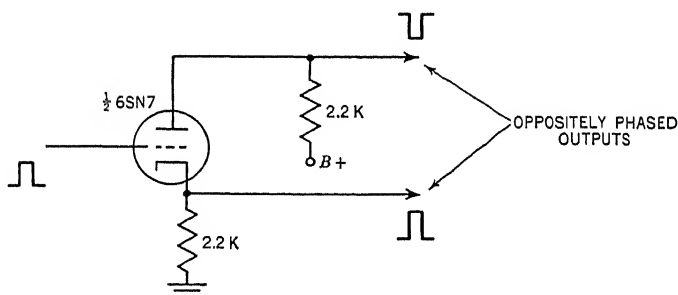
FIG. 33. A vacuum-tube phase inverter.

It is, of course, possible to obtain balanced signals of opposite polarity by using two transistor stages. One stage will serve to provide one polarity signal, while the other stage will take a portion of this signal, amplify it, and invert it and thereby provide the required second signal.

VOLUME-CONTROL PLACEMENT

In the amplifiers that were shown and discussed thus far, volume controls were omitted in order to keep the circuitry down to its essentials. However, volume controls are normally found in amplifiers, and it is important that we understand the do's and don't's of volume-control application.

Four examples of how volume controls may be wired into a circuit are shown in Fig. 34. In Fig. 34a and b, variation of the volume-
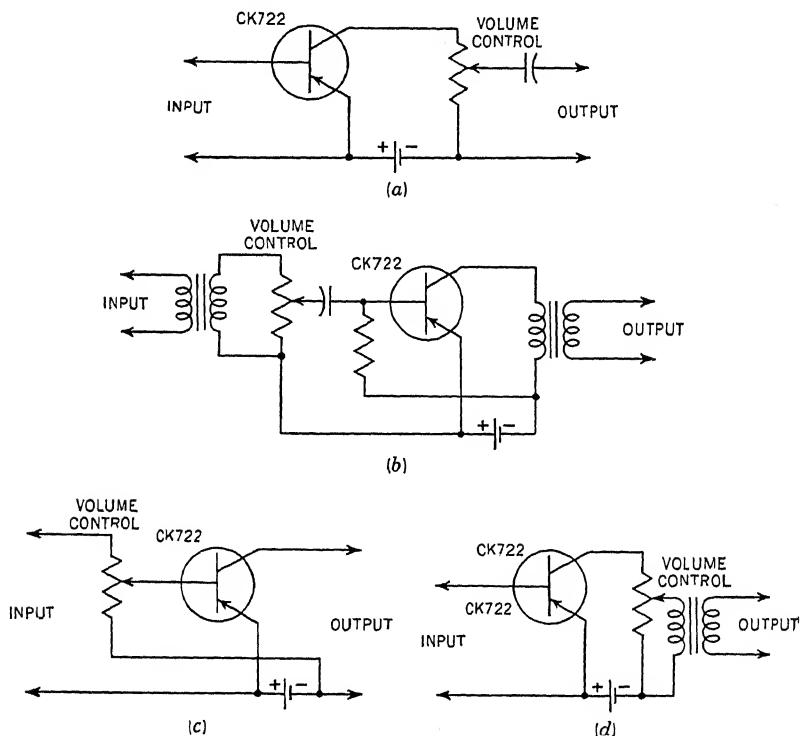
Fig. 34. Satisfactory (a and b) and unsatisfactory (c and d) methods of connecting a volume control into a transistor amplifier circuit.

control arm does not vary the base current, the collector current, or the value of the load as seen by the transistor. In the first case (Fig. 34a) we are varying the amount of voltage being taken from the load resistor; in the second instance (Fig. 34b) we vary the amount of signal voltage being fed to a transistor.

In the third and fourth illustrations of Fig. 34, rotation of the control arm will alter the operating conditions in the transistor amplifier. For example, in Fig. 34c, rotating the volume-control arm will vary the base current and with it, the collector current. In Fig. 34d, the volume control will vary both the collector current and load impedance. Hence, neither of the two latter arrangements would be desirable in actual circuits.

Tone controls present similar problems, and they, too, must be inserted so that they do not affect either the direct operating currents or the load impedance of a transistor.

RADIO- AND INTERMEDIATE-FREQUENCY AMPLIFIERS

It was indicated in Chap. 3 that in the early stages of transistor development, the point-contact transistor possessed a considerably higher cutoff frequency than the junction transistor. Hence, for applications above 100,000 cycles, the point-contact transistor was used exclusively. However, in recent years, high-frequency junction transistors have been developed and, because of their greater stability, higher efficiency, and lower noise, have largely supplanted point-contact transistors in commercial receiving equipment. While the operating frequencies of these junction transistors is still far below those attained by vacuum tubes, steady progress is being made, and in time high-frequency transistors suitable for the r-f stages of television and f-m receivers will become available. At the present time, commercial high-frequency transistor applications have been confined to radio receivers and to the lower frequency stages of television sets.

In applying transistors to r-f and i-f amplifiers, careful consideration must be given to their input and output impedances. This, of course, is similar to audio-frequency application. The problem, however, takes on added importance at the higher frequencies because of the lower gain per stage obtainable. Where before we could lose some gain and not miss it, now we must do everything we can to retain as much of it as possible.

Interstage Coupling Networks. The most common connection (for junction transistors) is the grounded emitter, and with this arrangement the input impedance is fairly low (on the order of 1,000 ohms or less) while the output impedance is in the neighborhood of 10,000 to 20,000 ohms. It is the purpose of the interstage coupling network

not only to provide whatever frequency selectivity is desired but also to match these input and output impedances.

There are a number of interstage coupling networks possible, and the more important of these are shown in Fig. 35.* In the first group (Fig. 35a) the second amplifier is connected directly into the parallel-resonant circuit, either in series with the inductance or in series with the capacitance.
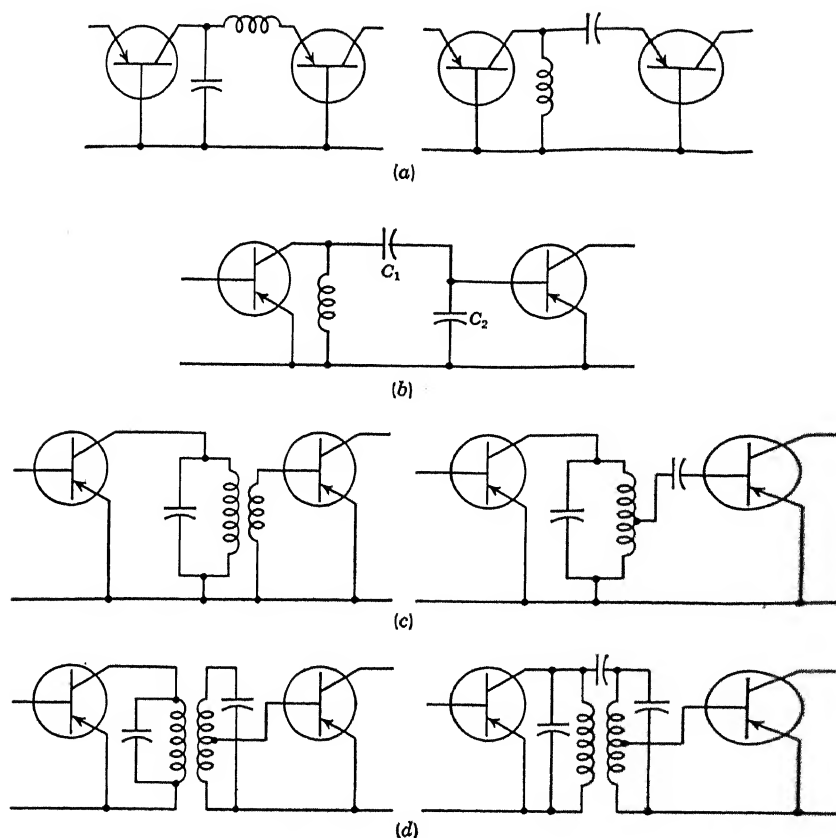
Fig. 35. Various methods of coupling transistor stages together.

In the second group (Fig. 35b) the second stage is connected to the junction of two capacitors C_1 and C_2, which resonate with the inductance. By properly proportioning the values of C_1 and C_2, we can use the network to match the high output impedance of the first transistor to the much lower input impedance of the second transistor.

* W. F. Chow, High-frequency Transistor Amplifiers, *Electronics*, April, 1954.

The third group (Fig. 35c) employs inductive coupling between stages. In the first illustration of Fig. 35c, the primary circuit is tuned, offering a high impedance to the first transistor stage. The signal is then transferred to an untuned secondary containing fewer turns. This step-down action enables the low-impedance input of the second transistor to match the output of the first stage. In the second illustration of Fig. 35c, we obtain the same electrical action by dispensing with the secondary winding and tapping directly into the primary inductance. In this arrangement, a coupling capacitor is needed to prevent the higher collector bias of the preceding transistor from reaching the base of the second unit.

In the final group of coupling networks (Fig. 35d) double tuning is employed. Again note how the second stage must be tapped down in order to achieve the proper impedance match.

Intermediate-frequency Amplifiers. A two-stage i-f system suitable for a broadcast receiver is shown in Fig. 36. The circuit uses two CK760 high-frequency PNP transistors in a grounded-emitter configuration.
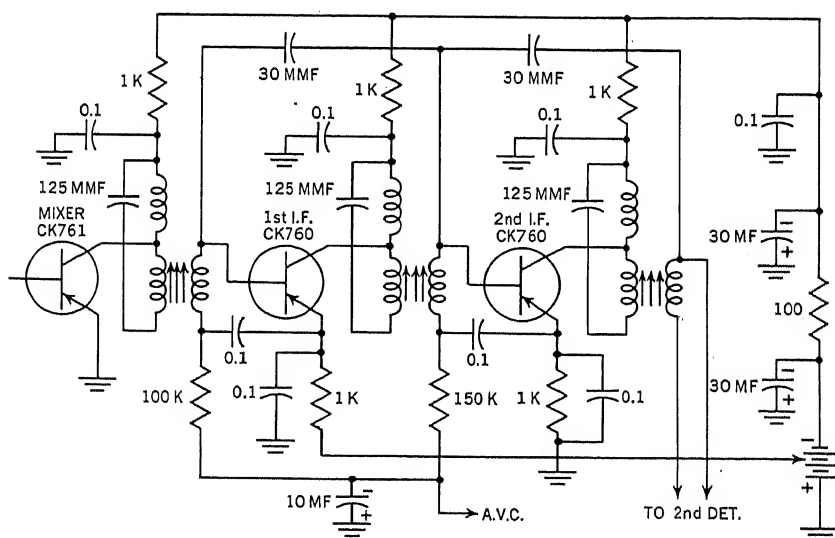
FIG. 36. A two-stage i-f system operating at 465 kc. (*Courtesy Raytheon Mfg. Co.*)

Operating frequency is 465 kc, and the over-all power gain is at least 50 db (ratio of 100,000 to 1). The i-f transformers have 155 total turns on the primary, tapped at 55 turns, with an 18-turn secondary. The

coils are bifilar wound and enclosed in an adjustable ferrite cup. They are tuned by a fixed 125-$\mu\mu$f capacitor across the primary.

Each emitter possesses a 1,000-ohm d-c stabilizing resistor. Alternating-current or signal degeneration is prevented by the use of 0.1-μf bypass capacitors across these resistors.

It will be noted that each i-f stage is neutralized by connecting a 30-$\mu\mu$f capacitor from the base of the following stage to the base of the preceding stage. (These two points are 180° out of phase because of the grounded-emitter arrangement.) Neutralization was deemed necessary because high-frequency transistors may become regenerative because of the value of the internal capacitances.

The bases of both i-f stages connect into an a-g-c line. Operation of this a-g-c system will be explained in Chap. 6 when the complete receiver (of which these i-f stages are a part) is examined.

Another two-stage radio-receiver i-f system is shown in Fig. 37. The transistors here, too, are connected with the emitters common to both
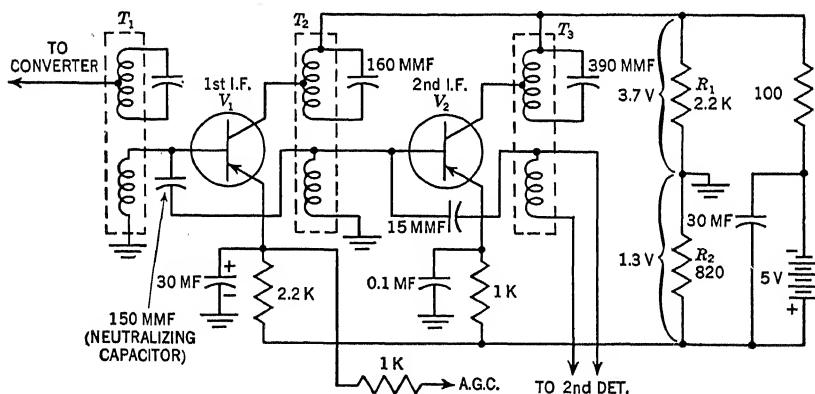
FIG. 37. A second i-f system designed for an a-m broadcast receiver.

input and output circuits. The i-f transformers T_1, T_2, and T_3 comprise three bifilar circuits which serve as interstage coupling networks, with essentially unity coupling between primary and secondary windings.

The first i-f transformer T_2 transfers the received signal to the base of the first i-f transistor V_1. Neutralization of this stage is achieved by the 150-$\mu\mu$f capacitor that connects from the base of V_2 to the base of V_1. The same stage (V_1) is provided with a-g-c bias that ties into the emitter, rather than the base, as in the previous circuit. The control action is accomplished by varying the direct emitter current of V_1 in

step with the signal level at the second detector. Figure 38 demonstrates what effect this variation has on the gain, and on the input and output impedances of the transistor. Note that transistor gain decreases rapidly as the direct emitter current drops below 0.25 ma. Observe, too, that the input and output impedances rise with emitter-current decrease, causing mismatching in the input and output circuits and further reducing gain.
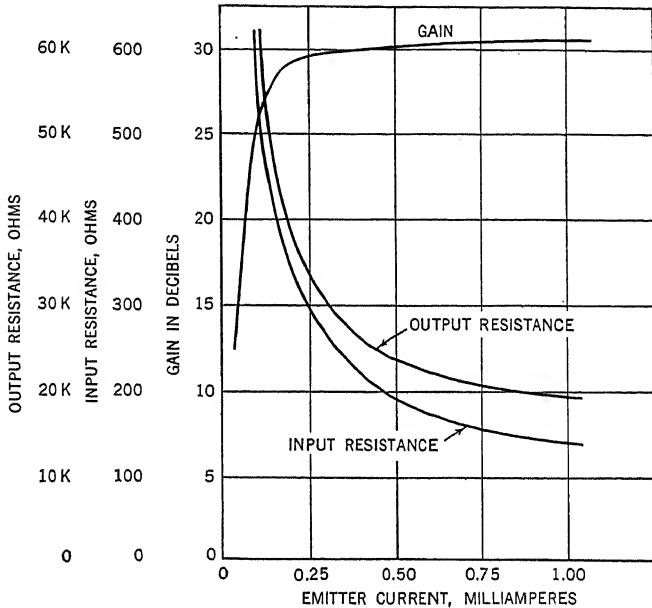
FIG. 38. Variation in input and output resistance of the first i-f stage in Fig. 37 with changes in emitter current. Variation in stage gain is also indicated.

In the second i-f stage we have essentially the same circuit arrangement, although there are some minor modifications. For one thing, the value of the neutralizing capacitor is reduced to 15-$\mu\mu$f; this is because the input impedance of the following second detector is higher and the turns ratio of the two windings of T_3 are more nearly equal. This increases the amount of signal voltage present across the secondary of T_3, and the value of the neutralizing capacitor is reduced accordingly.

A second change is the reduction in the value of the emitter resistor. This stems from the fact that a-g-c voltage is not fed back to this stage. Thus, in this i-f system, only one stage is gain controlled.

The d-c voltage distribution in this system makes use of a 5-volt bat-

tery and a resistance-divider network R_1 and R_2. The negative battery terminal connects to each collector, and the positive terminal to each emitter. The bases of the corresponding transistors are at d-c ground potential. By means of the divider network, each collector is made 3.7 volts negative with respect to its base; each emitter is only 0.1 volt positive with respect to its associated base because of the presence of the resistor in the emitter leg. That is, the current flowing between emitter and base produces a voltage drop across the emitter resistor that counteracts in large measure the 1.3-volt potential applied between these two elements.

Radio-frequency Amplifiers. The same considerations which govern the design of the i-f amplifiers also hold true for r-f amplification. However, because r-f amplifiers operate at higher frequencies, we can expect lower gain.

The r-f stage of a transistor automobile radio is shown in Fig. 39. The input transformer T_1 is slug tuned, with its slug mechanically
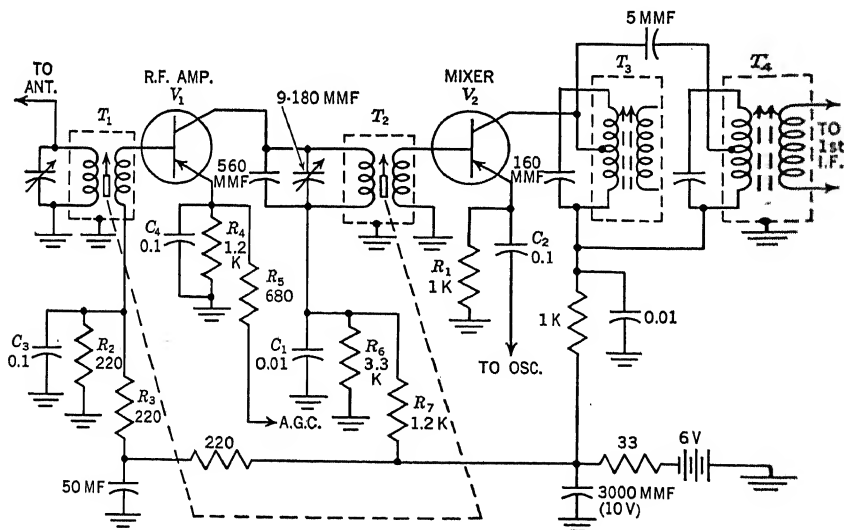
FIG. 39. The r-f and mixer stages of a transistor automobile radio.

ganged to those of the converter and the local oscillator (not shown) coils. The Q of T_1 varies from 70 to 50 across the tuning band, 550 to 1,600 kc. The base of V_1 is returned to the junction point of R_2 and R_3, where the d-c potential is approximately 1.5 volts. A d-c stabilizing

resistor R_4 is placed in the emitter leg of V_1 to make the stage relatively insensitive to changes in ambient temperature. A small 680-ohm resistor R_5 brings an a-g-c voltage to the emitter. If no a-g-c control is desired, the connection between R_4 and R_5 can be severed. C_4, across R_4, serves to place the emitter at r-f ground. C_3, at the junction of R_2 and R_3, serves also as a low-impedance path to ground for radio frequency.

The collector of V_1 connects to the primary of transformer T_2 and receives its d-c voltage from the junction of R_6 and R_7. Collector voltage is 4.5 volts, and C_1 ensures that the r-f signal will be shunted around the battery. Greater amplification could have been obtained from V_1 if the full 6 volts of the battery had been applied to the collector, but this would have tended to degrade the signal-to-noise ratio. Since the latter is particularly important in the r-f stage, the lower collector voltage was employed.

Transformer T_2 couples the signal from the r-f stage to the mixer. In the mid-frequency range of the broadcast band, the output impedance of V_1 is 10,000 to 15,000 ohms and the mixer input impedance is about 500 ohms. These are the two impedances that must be matched by T_2.

The r-f signal is applied to the base of V_2, while the locally generated oscillator signals is brought into the circuit by C_2 and developed across R_1. The latter resistor, incidentally, also serves to provide bias stability in the same manner as R_4 in the r-f amplifier stage. Approximately 0.4 volt rms of oscillator voltage is injected into the converter stage, this value having been found to provide optimum conversion gain of V_2. If the oscillator voltage is reduced below this level, the conversion gain drops rapidly, which means that we obtain a smaller i-f signal for a given amount of incoming r-f signal. On the other hand, if the oscillator signal is made larger than this optimum value, conversion gain will again decrease, although this time more slowly.

A fairly elaborate interstage coupling network is employed between the mixer and first intermediate frequency. This is designed to achieve the desired signal bandpass, with a fairly rapid fall-off on either side. Output impedance of the converter is in the neighborhood of 50,000 ohms, and it is not affected by signal frequency. Capacitor C_2 and the oscillator circuit that it ties into offer very low impedance to signals of intermediate frequency, so that for i-f signals, R_1 is effectively bypassed and no degeneration results.

Interstage coupling networks other than that shown in Fig. 39 could be employed between r-f stages. and those will follow closely the patterns indicated in Fig. 35.

QUESTIONS

1. How can you determine by looking at a schematic diagram whether a PNP or an NPN transistor is being employed? (Assume that this information is not indicated.)

2. Why do the coupling capacitors in transistor audio amplifiers possess high values?

3. Explain the purpose of C_2 and R_2 in Fig. 3.

4. Why must I_{co} be watched more closely in common-emitter amplifiers than in common-base amplifiers?

5. How is the effect of I_{co} minimized in common-emitter amplifiers?

6. Why is it more difficult to cascade transistor amplifiers than vacuum-tube amplifiers?

7. Why can more gain be obtained using transformer coupling between transistor amplifiers than RC coupling?

8. Draw the diagram of a two-stage transformer-coupled transistor amplifier.

9. Explain the purpose of each component in the foregoing circuit.

10. Draw the diagram of a three-stage RC-coupled transistor amplifier.

11. What considerations govern the choice of values for R_f and C_f in Fig. 13?

12. What advantages does negative feedback offer in transistor applications?

13. Illustrate a simple method of obtaining negative feedback.

14. Explain how negative feedback is obtained in the circuit of Fig. 14. Show that the feedback voltage is actually 180° out of phase with the voltage existing at the feedback point.

15. Would the operation of the circuit in Fig. 14 be altered if the feedback line terminated at the base of V_1 rather than at the emitter? Explain.

16. What do we mean by complementary symmetry in transistors?

17. Explain how the circuit in Fig. 19 operates.

18. Draw the diagram of a push-pull class A transistor power amplifier.

19. What advantages does class B operation offer over class A in the audio range?

20. How can the principle of complementary symmetry be used advantageously in push-pull amplifiers?

21. What precautions must be observed when incorporating a volume control into a transistor amplifier circuit?

22. Draw a transistor phase-inverter circuit. Explain how it operates.

23. Illustrate several suitable interstage coupling networks for transistor r-f and/or i-f amplifiers.

24. What is the purpose of the neutralizing circuits sometimes found in transistor i-f or r-f amplifiers?

25. How is neutralization achieved?

CHAPTER 5

TRANSISTOR OSCILLATORS

Transistors will function as oscillators as readily as they will as amplifiers. For every vacuum-tube oscillator, there is a transistor counterpart. In addition, transistors, particularly point-contact transistors, can be designed to produce oscillations in a way that cannot be duplicated with tubes.

Oscillations in vacuum-tube circuits are normally produced by feeding a portion of the amplified signal in the plate, or output circuit, back to the grid, or input circuit. The phase of this feedback signal must be the same as the instantaneous phase of the grid signal in order that the two will add and reinforce each other. This is in distinction to degeneration or negative feedback, where the returned signal is 180° out of phase with the existing grid signal.

LOW-FREQUENCY OSCILLATORS

A simple audio-frequency oscillator, using a vacuum tube, is shown in Fig. 1. The transfer of energy from the plate to the grid is achieved through transformer T_1. The primary and secondary sections are so connected that the field set up by the secondary winding establishes an induced voltage in the primary which tends to maintain oscillations in the circuit. To appreciate the importance of winding polarity, all one has to do is reverse the connections to either T_1 winding and the oscillations cease. (Of course, if the connections to both windings are reversed, circuit behavior will be unaffected.)

FIG. 1. A simple vacuum-tube audio-frequency oscillator.

The cathode of the oscillator tube is grounded, and grid bias is developed by the combination of C_1 and R_1. With this type of biasing,

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the circuit operates class C, which means that plate current flows in
pulses for only a short time during each signal cycle. If desired, the
tube can be made to function as a class A oscillator by moving C_1 and
R_1 into the cathode circuit.

An equivalent transistor oscillator, using the same general arrange-
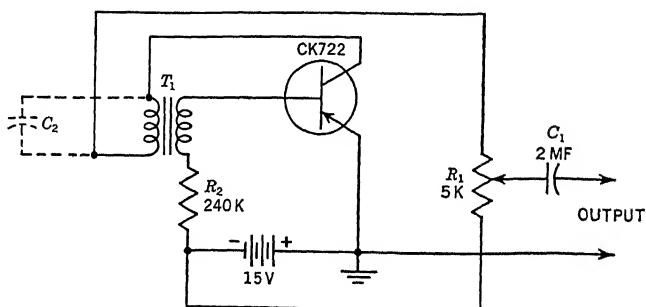
FIG. 2. A transistor audio-frequency oscillator.

ment of components, is shown in Fig. 2. An output control R_1 with an
output coupling capacitor C_1 has been added to indicate one way in
which an output signal could be obtained from this circuit. One bat-
tery is employed to bias both collector and base circuits. R_2 is inserted
in the base lead to limit the voltage between base and emitter to the
proper value dictated by this transistor.

In the design of this oscillator, the windings on the transformer T_1
must match the low impedance of the base-emitter circuit on the one
hand and the high impedance of the collector circuit on the other. The
problem, in this respect, remains similar to what it is in amplifiers.
Frequency of oscillation will depend upon the inductance of the wind-
ings and their distributed capacitance, and it may be lowered by
shunting capacitors (such as C_2) across the high-impedance collector
winding.

The same oscillator, using the transistor in a grounded-base arrange-
ment, is shown in Fig. 3. Two batteries are required effectively to bias
input and output circuits with the proper polarity.

Another low-frequency transistor oscillator, this time using an in-
ductor having a single winding, is shown in Fig. 4.* A Raytheon
CK722 PNP transistor is used. Feedback of in-phase energy from the
collector to the emitter is achieved by capacitors C_1 and C_2 in what
is essentially a Colpitts circuit arrangement.

* L. Fleming, Transistor Oscillator Circuit, *Electronics*, June, 1953.

Resistor R_1 determines the bias between the emitter and base, and therefore it will govern the extent of current flow through this portion of the circuit during each cycle of oscillation. Any value between 5,000 and 100,000 ohms will work. Resistor R_2 is designed to limit the reverse collector current flow during that part of the half cycle when the
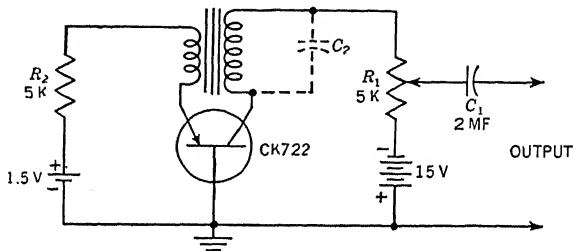
FIG. 3. The same oscillator as in Fig. 2 in a grounded-base arrangement.

collector is driven positive. If R_2 is made zero, the positive peaks of the voltage wave will have flat tops because the collector is driven to overload. The waveform is found to improve as R_2 is increased to a thousand ohms or so, and thereafter improvement occurs more slowly as the resistance is raised. When the value of R_2 reaches around 40,000 ohms, the collector voltage is reduced to such an extent that oscillations cease.
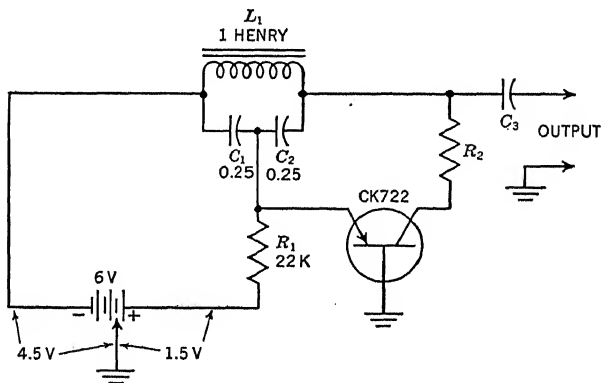
FIG. 4. A transistor oscillator using a Colpitts circuit arrangement.

The values of C_1, C_2, and L_1 shown in Fig. 4 will produce a 1,000-cycle signal. Battery drain is less than 50 μa. The upper frequency limit for this transistor in this circuit is in the neighborhood of 50 kc.

For those readers who might find that a comparison of a vacuum-tube Colpitts oscillator makes this circuit easier to understand, the circuit of Fig. 5 is shown. The main feature to look for in both circuits is the way the frequency-determining components (i.e., L_1, C_1, and C_2) are connected. The voltages in the vacuum-tube circuit would obviously be applied differently from the bias voltages of the transistor. This difference, therefore, must be discounted. (Strictly speaking, the circuit of Fig. 5, to be directly equivalent to the oscillator in Fig. 4,
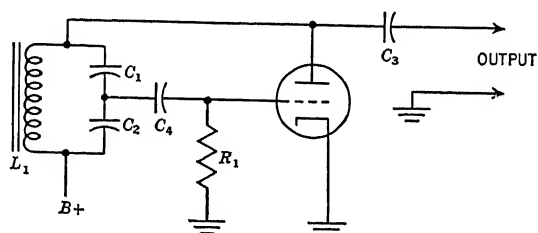
FIG. 5. A vacuum-tube Colpitts oscillator.

should have its grid grounded and the cathode connected to the junction of C_1 and C_2. However, the arrangement in Fig. 5 is the one most frequently used and undoubtedly the most familiar one to the reader.)

The employment of a transistor as a blocking oscillator is illustrated in Fig. 6. This circuit is closely similar to that shown in Fig. 2 except
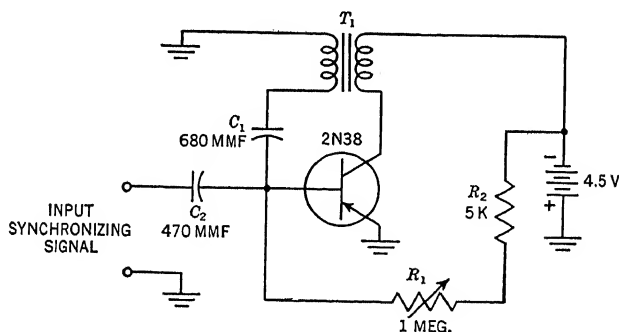
FIG. 6. A blocking oscillator.

for the addition of a small coupling capacitor C_1 between the base and T_1. The frequency of the circuit is variable between 3 and 60 kc and is inversely proportional to $R_1 R_2 C_1$. The blocking oscillator can be synchronized to a pulse or a sine-wave input by coupling the signal to

the base through capacitor C_2. Note the extreme simplicity of this circuit, including the manner in which one battery furnishes power to the entire circuit.

Another common vacuum-tube oscillator, particularly in television receivers, is the multivibrator. The basic form of this oscillator is shown in Fig. 7 and is seen to consist of two resistance-capacitance-
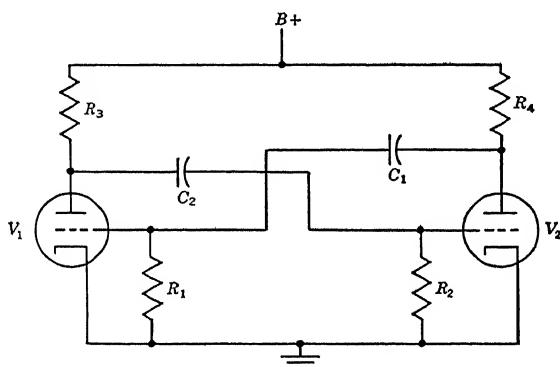
FIG. 7. The basic multivibrator circuit using vacuum tubes.

coupled amplifiers with the output of the second stage fed back to the input of the first stage. Oscillations occur in this system because each tube reverses the voltage applied to its grid by 180° and two such reversals produce a signal at the plate of V_2 which is in phase with the voltage at the input of V_1.

In a multivibrator, one tube is cut off while the other one is conducting. How long this condition persists is determined largely by the values of the grid resistors and capacitors R_1, R_2, C_1, and C_2. To see how the shift in conduction is made from tube to tube, let us briefly follow one cycle in the operation of a multivibrator. Assume that the power supply has just been connected across the circuit. Owing perhaps to some slight disturbance in the circuit, the plate current of V_1 increases. This produces an increase in the voltage across R_3, with the plate end of the resistor becoming more negative. Capacitor C_2, which is connected to R_3 at this point, likewise attempts to become more negative, and the grid of V_2 also assumes the same potential. The net result is a lowering of the current through V_2 and R_4.

The lowered voltage across R_4 means that the plate end of this resistor becomes less negative, or relatively positive to its previous value. Capacitor C_1 transmits this positive increase to the grid of V_1,

and consequently, even more plate current flows through R_3. The process continues in this manner, with the grid of V_1 becoming more and more positive and driving the grid of V_2 increasingly negative by the large negative charge built up across R_2 and C_2. The plate current of V_2 is rapidly brought to zero by this sequence of events.

Tube V_2 remains inactive until the negative accumulation of charge on C_2 discharges and removes some of the large negative potential at the grid of V_2. The path of discharge of C_2 is through the relatively low resistance of r_p of V_1 and the relatively high resistance R_2. When C_2 has discharged sufficiently, plate current starts to flow through R_4, causing the plate end of the resistor to become increasingly negative. This now places a negative charge on the grid of V_1, and the plate current through R_3 decreases. The reduction in the voltage drop across R_3 causes the plate end of the resistor to increase positively, and the grid of V_2 (through C_2) receives this positive voltage. The increased current through R_4 quickly raises the negative grid voltage on V_1 (through C_1) and drives this tube to cutoff. When the excess charge on C_1 leaks off, the process starts all over again. C_1 loses its accumulated negative charge by discharge through r_p of V_2 and R_1.

The entire operation may be summed up by stating that first the plate current of one tube rises rapidly, driving the second tube to cutoff. This condition remains until the second tube is released from its cutoff state and starts to conduct. It is now the first tube which is cut off. When the first tube is again permitted to conduct, the second tube is driven into nonconduction. The switching continues in this manner, with the rapidity of turnover (i.e., frequency) determined by the grid resistors and capacitors.

An equivalent multivibrator, using transistors, is shown in Fig. 8.
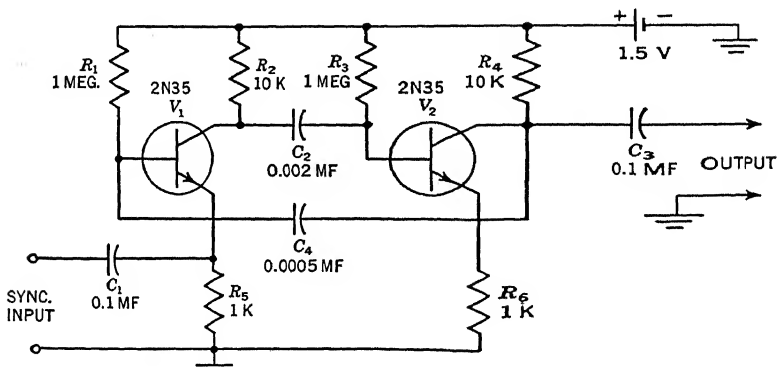
FIG. 8. A transistor multivibrator. The 2N35 transistors are of the NPN variety. (*Courtesy Sylvania Electric Products, Inc.*)

Each transistor must be connected as a grounded-emitter amplifier in order to provide the necessary 180° phase reversal in each stage. For the values of the components as shown, the repetition frequency is on the order of 2 kc. It is possible by altering these values to reach frequencies of several hundred kilocycles.

The battery voltage is 1.5 volts, and the total current drain is 250 μa. Under these conditions, an open-circuit rectangular wave will be obtained having an amplitude of 1.4 volts peak to peak. Positive synchronization can be obtained by injecting a 5-volt rms signal at the sync input terminals.

Cutoff of a single stage is achieved in this multivibrator in exactly the same way that it is in the vacuum-tube multivibrator. For example, V_2 in Fig. 8 is cut off when the emitter-base voltage is such that the base is negative with respect to the emitter. Normally, the base should be positive with respect to the emitter because the 2N35 transistor is an NPN unit. The negative potential required by the base for effective cutoff is developed across resistor R_3. And V_2 remains cut off until the negative charge held by C_2 (and applied across R_3) has been reduced through discharge. For transistor V_1, the controlling components are C_4 and R_1.

If a saw-tooth wave is desired across the output terminals instead of a rectangular wave, it can be obtained by connecting a capacitor from the collector of V_2 to ground.

A cathode-coupled multivibrator using a minimum of parts is shown in Fig. 9. This is closely related to the vacuum-tube multivibrator of Fig. 10, a circuit that is employed extensively in television receivers.
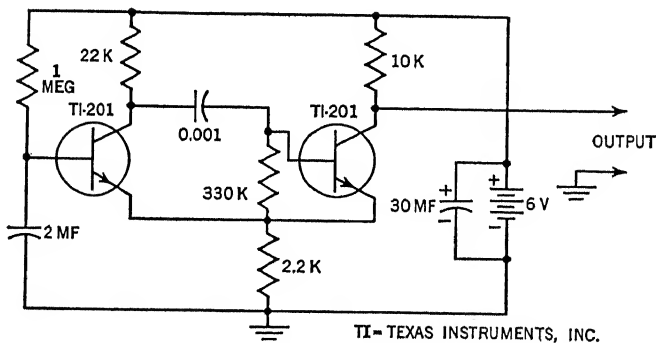
FIG. 9. A cathode-coupled multivibrator using a minimum of parts. The type 201 transistors are NPN units, and they are manufactured by Texas Instruments, Incorporated. Equivalent PNP transistors may also be employed if the battery leads are reversed.
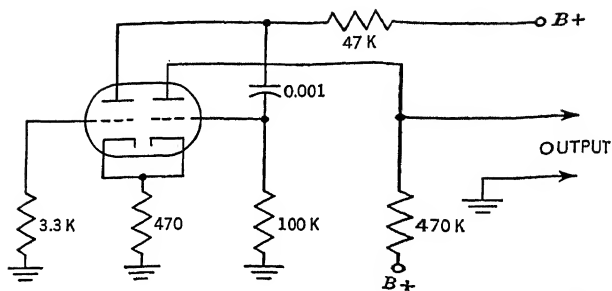
FIG. 10. A vacuum-tube cathode-coupled multivibrator.

RADIO-FREQUENCY OSCILLATORS

The use of transistors in r-f oscillators, as distinguished from the foregoing low-frequency oscillators, is governed by the same considerations with the addition of frequency limitation imposed by the transistor itself. As indicated in Chap. 3, considerable progress is being made in developing junction transistors which can operate consistently in the megacycle region. In terms of actual operating frequencies achieved, the results may appear somewhat disappointing when compared with the frequencies which vacuum tubes can generate. However, when one stops to remember that the transistor is barely 10 years old and it was just recently that the upper limit for junction transistors was less than 200,000 cycles, the rapidity and extent of the advance can be considered as nothing short of phenomenal. With such remarkable progress in the past, it is safe to be optimistic about the future.

An r-f oscillator which is a direct outgrowth of the audio oscillator of Fig. 2 is shown in Fig. 11. L_1 and L_2 are two tightly wound coils
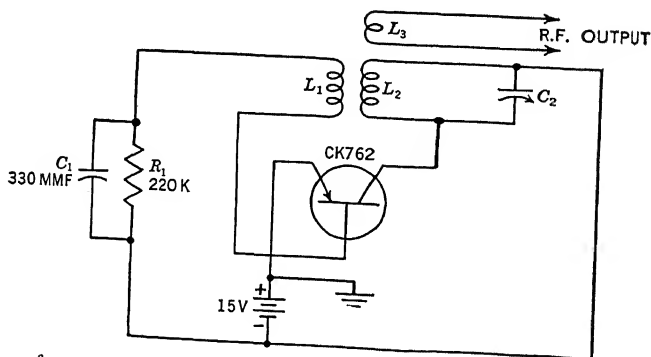
FIG. 11. An r-f transistor oscillator. The CK760 is an alloy junction transistor with a cutoff frequency of 20 Mc.

which provide for the transfer of energy between output and input circuits. L_3 is wound close to L_2, and the energy it absorbs is transferred to whatever output circuit is connected to the oscillator. Capacitor C_2 tunes L_2 and enables the generated frequency to be
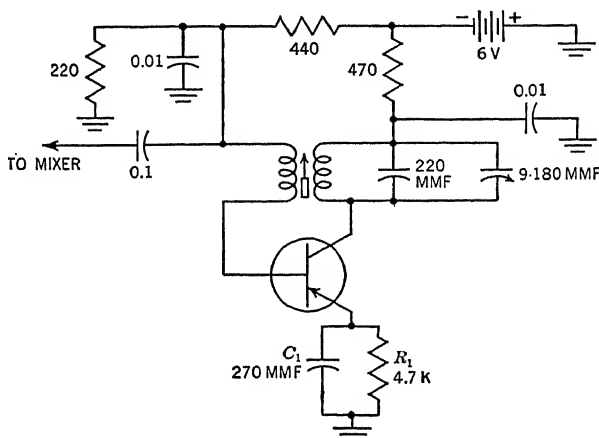
FIG. 12. An oscillator that was designed for a transistorized automobile receiver.

varied. R_1 serves to limit the emitter current to a safe value; C_1 across R_1 assists in the oscillating action.

The oscillator shown in Fig. 12 is similar to the preceding circuit except that a 4,700-ohm resistor and a 270-$\mu\mu$f capacitor are inserted in
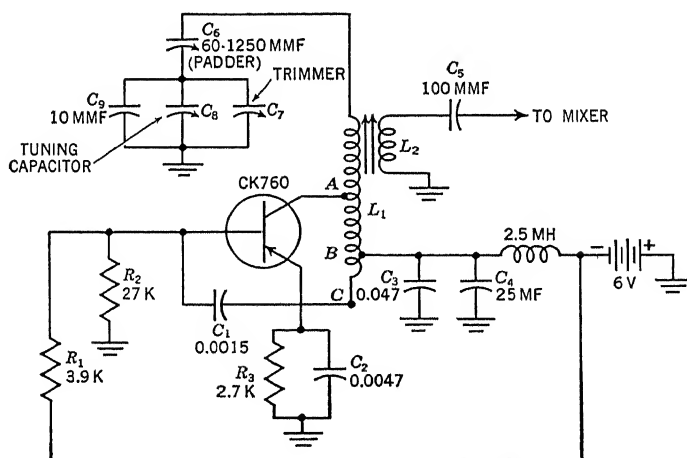
FIG. 13. An r-f oscillator employed in a radio receiver.

the emitter lead. This particular oscillator is employed as the local oscillator in a broadcast receiver, and the R_1C_1 network is used to introduce a limited amount of degeneration into the circuit. This offsets some of the positive, regenerative feedback and serves to reduce the loading effect of the transistor input circuit on the oscillator tuned circuit. It was found that when this was done, oscillator tuning became relatively independent of the transistor input impedance. A further aid to stability is the use of a relatively high tank capacitance across the collector tuned circuit.

Another oscillator which has been employed in a radio-broadcast receiver is shown in Fig. 13. If we ignore, for the moment, the turns on L_1 which extend above point A, and if we also disregard winding L_2, then what we have here is a Hartley oscillator (see Fig. 14). The
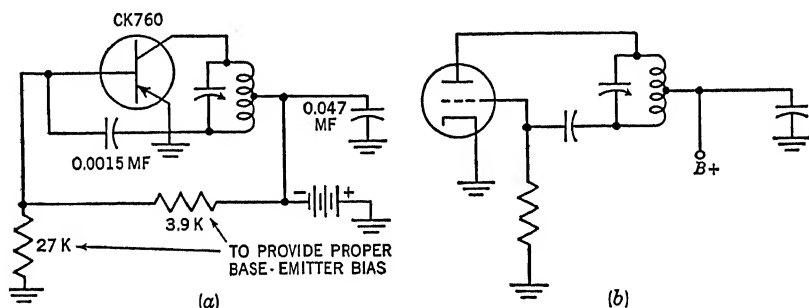
FIG. 14. A Hartley oscillator using (a) a transistor and (b) a vacuum tube.

voltage which is developed between points B and C of L_1 represents the energy which is fed back to the base input circuit via coupling capacitor C_1.

The collector is tapped down on L_1 to decrease the effect of its (i.e., the collector) capacitance, to provide a better impedance match between the transistor and the tuned circuit, and to improve frequency stability and tracking. (The last feature stems from the application of this oscillator in a radio receiver.) Tracking also explains the reason for the presence of C_6 (600 to 1,250 $\mu\mu f$) and C_9 (10 $\mu\mu f$). In this particular design three-point tracking between oscillator and mixer was obtained by using a slug in the oscillator coil, a padder capacitor C_6, and a gang capacitor trimmer C_7. The slug takes care of the central portion of the band, the padder provides an adjustment at the low end of the band, and the trimmer is employed to make the high end of the tracking curve fall into line.

Energy from the oscillator is transferred into the mixer circuit (not shown here) by a combination of inductive and capacitive coupling. The initial transfer from L_1 to L_2 is inductive; the second transfer, from L_2 through C_5 to the mixer, is capacitive. The designers of this circuit felt this arrangement would provide a more nearly constant oscillator injection voltage at the mixer.

The necessary biasing voltage for the transistor collector is brought in through coil L_1. A similar biasing voltage for the base is brought in via R_1 and R_2. The resistor (R_3) and capacitor (C_2) in the emitter leg serve approximately the same purpose here that they did in the previous oscillator circuit.

A transistorized Colpitts oscillator is shown in Fig. 15.* The single tuning circuit L_1 and C_1 is connected in the collector circuit between the collector element and the battery. To provide the proper feedback to sustain oscillations, 22-$\mu\mu$f capacitors are connected between collector and emitter and between emitter and ground. R_1 and R_2 provide the proper voltage for the base-emitter circuit, while R_3 functions as a d-c stabilizing resistor (to minimize the effects of temperature variations). With a 22½-volt supply, oscillations up to 15 Mc
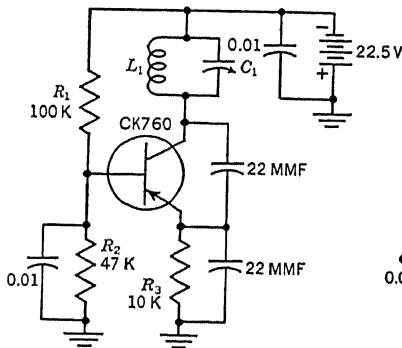
Fig. 15. A Colpitts oscillator using a transistor.
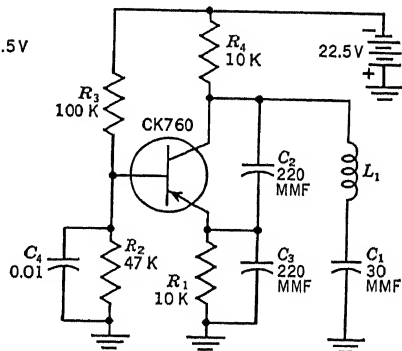
Fig. 16. A Clapp transistor oscillator (similar to the oscillator shown in Fig. 15).

were obtained with some CK760 transistors. The average maximum frequency of a number of such transistors was 7 Mc.

Another oscillator which is somewhat similar to the Colpitts oscillator but more stable is shown in Fig. 16. This is the Clapp oscillator, named after its originator J. K. Clapp. The tuning circuit C_1 and L_1 is

* P. G. Sulzer, Junction Transistor Circuit Applications, *Electronics*, August, 1953.
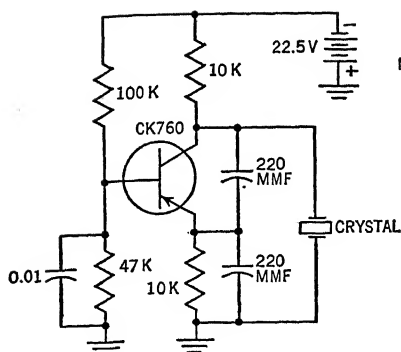
FIG. 17. A crystal-controlled Clapp oscillator.
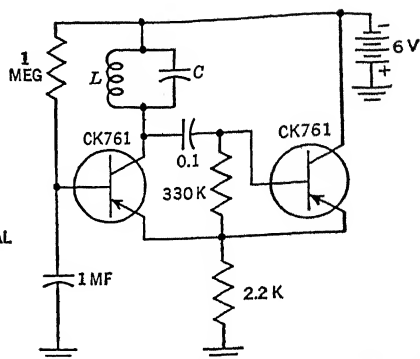
FIG. 18. A cathode-coupled sine-wave oscillator.

series resonant, and it is connected between collector and ground. Feedback voltage between the collector, emitter, and base is provided by C_2 and C_3. The remaining components of this circuit serve the same function as in the previous oscillator.

The same Clapp oscillator with a crystal substituted for the series-resonant circuit is shown in Fig. 17.

A cathode-coupled multivibrator was previously shown in Fig. 9. The same circuit modified for sine-wave oscillation is shown in Fig. 18. The resistor in the collector circuit of the first transistor is replaced here by a tuned circuit. With the choice of suitable junction transistors, oscillations above 10 Mc can be readily obtained. The vacuum-tube counterpart of this circuit will oscillate up to 80 Mc just as readily as it will at 1,000 cycles.
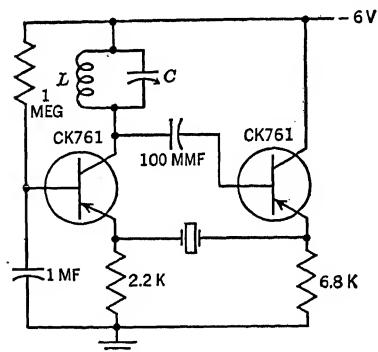
FIG. 19. A cathode-coupled sine-wave oscillator that is crystal controlled. Resonant frequency of the crystal should be the same as the resonant frequency of the parallel-resonant network, LC.

Crystal control can be incorporated into this oscillator by connecting a series-resonant crystal between the emitters of the two transistors (see Fig. 19).

Considerable work has been done with transistorized crystal oscillators because of their inherent frequency stability. A crystal oscillator that was developed at the National Bureau of Standards is shown in Fig. 20. A PNP junction transistor is used, together with a 100-kc crystal. Bias battery voltage is only 1.5 volts. Current drain is 100 μa.

The 0.01-μf capacitors connected to ground from each side of the crystal serve to maintain a constant phase shift in the crystal feedback loop. The crystal itself is placed in the path between collector and base. The transistor is operated as a grounded emitter, and it develops 0.8 volt across the 100-kc tuned circuit connected to the collector. Driving current for the crystal is obtained from a capacitive voltage divider consisting of the 40-$\mu\mu$f and 0.01-μf capacitors connected in series between the collector and ground.

P-N-P
TRANSISTOR

22 K 0.01 MF 100 MMF OUTPUT

100

- 1.5 V

0.01

6 MH 350 MMF

100 KC
TUNED CKT

100 KC 100 K

0.01 MF

40 MMF
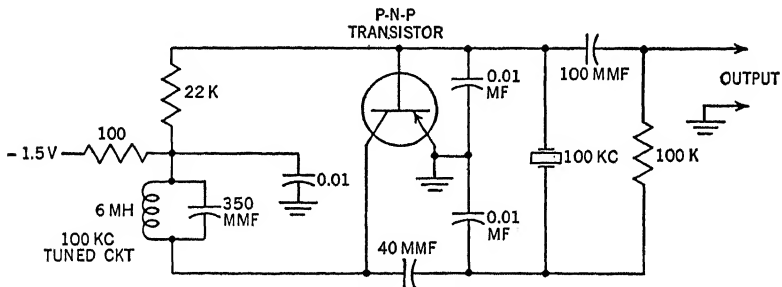
FIG. 20. A highly stable transistor oscillator developed at the Bureau of Standards.

The stability of this oscillator is excellent. Measurements of frequency with changes in temperature and voltage indicate that the frequency varies approximately 1 part in 100 million per degree centigrade and 1 part in 100 million per 0.1 volt. Short-time variations are about $+3$ parts in 10,000 million, and long-interval drift indicates changes of about 3 parts in 1,000 million (i.e., 1 billion) per 24 hr.

Low-distortion Oscillator. Transistor oscillator circuits can be designed simply, as illustrated by the preceding arrangements, or they can be incorporated in more complex designs. A low-distortion audio oscillator employing three transistors is shown in Fig. 22. To appreciate the operation of this circuit, it may be instructive to commence with a simplified version of its vacuum-tube predecessor (Fig. 21a). The first tube V_1 is a vacuum-tube amplifier; the second tube is a cathode follower. Positive feedback, necessary to maintain oscillations, is fed from the cathode of V_2 to the cathode of V_1 through a lamp.* For stability, negative feedback is transferred from the same point on the cathode of V_2 to the control grid of V_1. A bridged-T network in this path produces

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* A lamp is used, instead of a conventional resistor, to stabilize the amplitude of the generated oscillations. Lamp-filament resistance rises with current, tending to maintain a constant positive-feedback voltage.
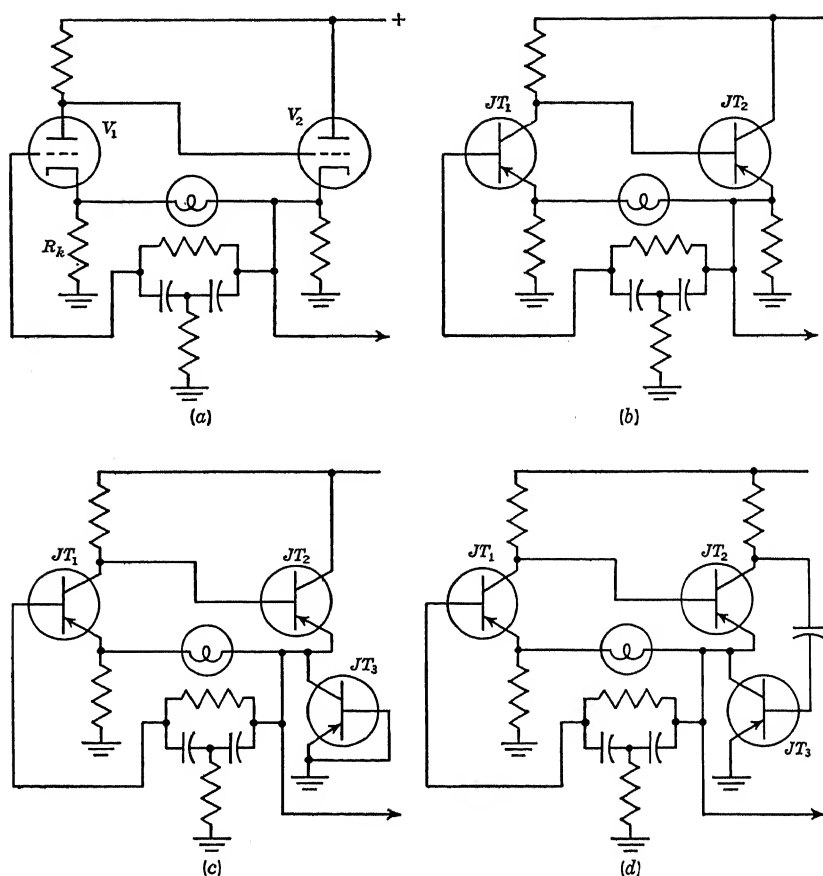
Fig. 21. The various steps in the development of a transistor oscillator from a vacuum-tube circuit. (*Courtesy Electronics.*)

a voltage minimum and zero phase shift at the operating frequency. At all other frequencies, more voltage passes through the bridged-T network, increasing the degeneration and discouraging oscillation. In essence, then, what we have here is a bridge arrangement in which oscillations will develop when the positive feedback exceeds the negative feedback, and the frequency at which this occurs is determined by the bridged-T network.

The first step in the development of the transistor circuit is shown in Fig. 21b. The first stage is a grounded-emitter amplifier. This is a direct counterpart of vacuum-tube V_1. The second transistor is operated as a grounded-collector stage, and it is equivalent in its action to the cathode follower V_2.
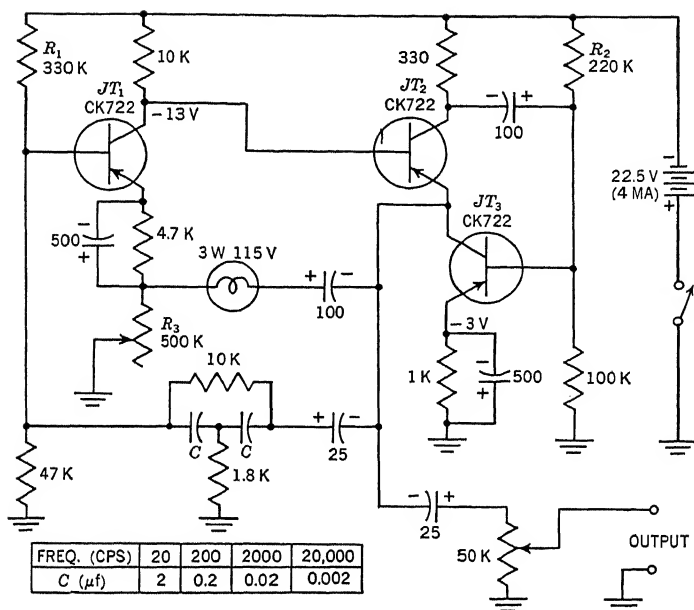
FIG. 22. Completed circuit of low-distortion transistor a-f amplifier. (*Courtesy Electronics.*)

An improved version of the oscillator is shown in Fig. 21c. The emitter load resistor of the second junction transistor JT_2 was replaced by a third transistor JT_3. This change was made because the high dynamic collector resistance of JT_3 permits more efficient operation of JT_2.

The third step in the development of this circuit (Fig. 21d) was made to reduce the amount of even harmonics present in the oscillator output signal. The base of JT_3 is connected to the load resistor of JT_2, effectively placing the two transistors in push-pull. When the collector current of one transistor increases, the collector current of the other decreases. The signal currents of both transistors flow through the same load resistor, and this provides for a high output current.

In the final version of this oscillator (Fig. 22) d-c stabilizing resistors were placed in series with the emitters of JT_1 and JT_3. Additional resistors, such as R_1 and R_2, establish the proper base operating voltages.

POINT-CONTACT TRANSISTOR OSCILLATORS

All the oscillator circuits discussed thus far have employed junction transistors. This is done for two reasons: First, oscillator circuits using junction transistors more nearly resemble vacuum-tube oscillators than

point-contact transistors. Second, in the commercial transistor equipment which the service technician will come in contact with, he is far more likely to find junction transistors in the oscillator stages than point-contact transistors. However, now that a number of representative junction transistor oscillator circuits have been examined, let us consider point-contact transistor oscillators.

In the previous discussion of point-contact transistors, mention was made of the fact that under some conditions, they tend to develop negative input and output resistances. This is because of the current gain that takes place between emitter and collector and, further, because the internal and external base resistances are common to both input and output circuits. In a junction transistor, the same common-base resistances exist, but the current gain (between emitter and collector) is always less than 1. Without the latter condition, negative resistance cannot develop under the same conditions.

There are three conditions under which a point-contact transistor will exhibit negative resistance. A negative resistance will appear if the base resistance is made high enough. And it will also appear if the emitter or collector resistances are made low enough with respect to the base resistance. Note that each of these factors may be dealt with separately or in combination. That is, either the external emitter resistance may be lowered, the external collector resistance may be lowered, or both may be lowered. Or we may lower one of these resistances while raising the base resistance. In any event, when the oscillatory condition, as specified by the transistor design equation, is satisfied, the circuit will exhibit negative resistance and it can be made to oscillate. (By the same token, we may counteract the oscillatory effect of a high base resistance by increasing the external emitter and collector resistances. In this case, we desire to prevent oscillations, for example, when a point-contact transistor is to be used as a straight amplifier.)

From the foregoing considerations, the construction of a point-contact transistor oscillator becomes a simple matter. For example, a sine-wave oscillator is shown in Fig. 23. A parallel-resonant circuit is connected to the base. The emitter is biased in the forward direction, while the collector is biased in the reverse direction.* At the resonant frequency of L_1 and C_1, a high impedance will be presented to the base, and since this is one of the conditions for developing a negative base resistance, oscillations will occur.

* An N-type point-contact transistor is assumed in the following discussion. See comments concerning P-type point-contact transistors in final paragraph of Chap. 2.

The circuit is exceedingly simple. In addition to the resonant circuit, there are two current-limiting resistors R_1 and R_2. Signal output can be obtained by coupling a small loop to L_1 of the resonant circuit. It is also possible to obtain signal output by capacitive coupling to the collector load resistor R_2.

The range over which this circuit will oscillate is determined by its emitter-to-base voltage. It is possible to stop oscillations by making the emitter negative with respect to the base instead of positive to it. However, if we now apply a positive pulse to the emitter, the circuit will oscillate for the duration of this trigger pulse provided the pulse amplitude is great enough to bring the instantaneous emitter-to-base voltage into the region where oscillations will occur.

It is possible to turn the circuit of Fig. 23 into a frequency multiplier (see Fig. 24). The resonant circuit which is tuned to the funda-
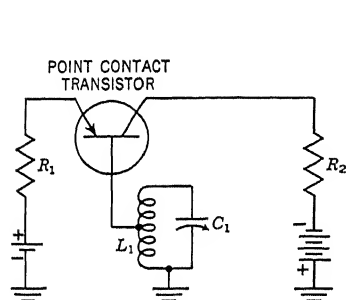
FIG. 23. A sine-wave oscillator using a point-contact transistor. Note that a junction transistor will not produce oscillations in this circuit.
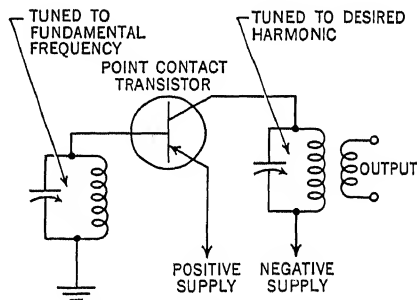
FIG. 24. A frequency-multiplier circuit.

mental frequency is placed in the base circuit, while the resonant circuit tuned to a desired harmonic of this frequency is placed in the collector circuit. With this arrangement the impedance (at the fundamental operating frequency) is high in the base circuit and low in the collector circuits. The parallel-resonant circuit in the collector lead may possess a high impedance at the harmonic frequency, but its impedance at the fundamental frequency is low. It is with the latter frequency that both the collector and base arms of the transistor are most concerned.

An oscillator may also be formed by lowering the emitter resistance. In the circuit of Fig. 25, a series-resonant circuit is connected between emitter and ground. At its resonant frequency, the impedance of the

series-resonant network drops down to a very low value and oscillations ensue. The resistor in the base circuit is chosen to meet further the conditions for oscillations, and it serves to stabilize operation. Resistors R_1 and R_2 are current-limiting resistors, designed to place the proper d-c bias voltages on the emitter and collector electrodes.
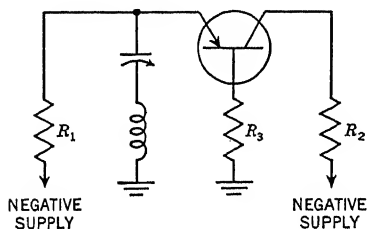
FIG. 25. A sine-wave oscillator in which a series-resonant circuit is placed between emitter and ground.
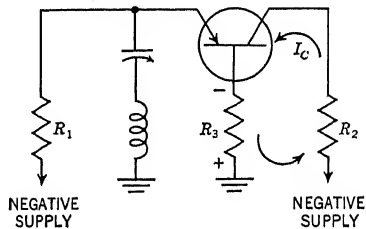
FIG. 26. Collector current flow in the circuit of Fig. 25. A negative voltage is applied to the emitter to counteract some of the voltage developed across R_3.

An interesting feature of this particular circuit is the application of a negative d-c voltage to the emitter. For circuit operation, the emitter should be biased slightly positive with respect to the base. The reason for the negative voltage is the high base resistance. When the collector current flows through this resistor, it develops a voltage which possesses the polarity shown in Fig. 26. The base end is made quite negative with respect to ground and, in this circuit, quite negative with respect to the emitter. Or looking at it in another way, the emitter is made considerably positive by this voltage drop across R_3. It is the purpose of the negative d-c voltage applied to the emitter to reduce this positive emitter potential to the desired level.

A variation of the foregoing circuit is given in Fig. 27. Here the
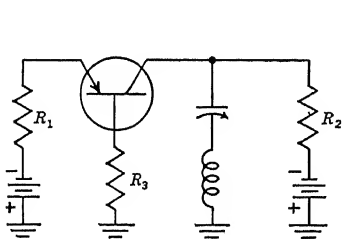
FIG. 27. A sine-wave oscillator in which the series-resonant circuit is connected between collector and ground.
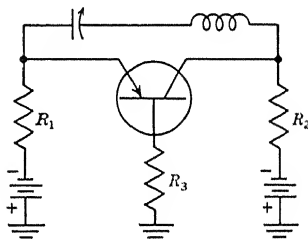
FIG. 28. An oscillator which combines many of the features of the oscillators in Figs. 25 and 27.

collector impedance is made low at the resonant frequency of the series-resonant collector circuit. Still another variation that combines many of the features of Figs. 25 and 27 is shown in Fig. 28. Here a series-resonant circuit is connected directly between emitter and collector. Note that in this oscillator, as in the previous two, a negative biasing potential is applied to the emitter to counteract the rather large positive voltage it receives from the base resistor. It is possible under some conditions to operate these oscillators with little or no resistance in the base circuit; in this case the emitter biasing voltage would have to be made positive.

Mention should be made again of the fact that the choice of resistance values in emitter, base, and collector circuits is governed by the design equations relating to this circuit. They must be chosen in accordance with these considerations, and it is readily possible to vary biasing voltages or the various resistances so that no oscillations occur. Hence, there is more involved than simply inserting a high impedance in the base circuit or low impedance in the emitter or collector circuits.

The foregoing oscillators tend to be frequency sensitive with respect to the applied voltages. To overcome this and achieve much greater frequency stability, crystals may be combined with each of the circuits. In Fig. 29, for example, the crystal is placed in the collector
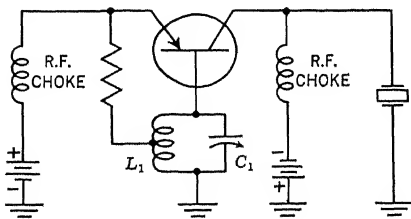
Fig. 29. A crystal-controlled oscillator using a point-contact transistor.
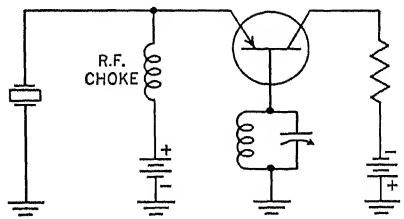
Fig. 30. A crystal-controlled oscillator with the crystal placed in the emitter circuit.

circuit, while the parallel-resonant circuit is placed in the base lead. Regeneration in this circuit is enhanced by the addition of voltage feedback through the emitter resistor which is tapped onto the oscillatory tank circuit. The size of the resistor has a very large influence on the upper frequency limit of this oscillator. As the resistance is increased, the upper frequency of oscillation increases, but beyond a certain optimum value, the upper frequency limit decreases.

In the design of the circuit of Fig. 29, care must be taken to make the collector impedance high so that the crystal is not loaded down

too much. The frequency of oscillation of L_1C_1 is made equal to that of the crystal.

Note that the emitter element connects to the positive terminal of the bias battery. Although the a-c impedance in the base circuit is high, its d-c resistance is low. Consequently, very little d-c voltage appears in the base circuit and the emitter-to-base bias is established almost completely by the emitter battery.

In Fig. 30, the crystal is shown connected to the emitter. Here the conditions must be chosen so that the emitter impedance is made high enough to match that of the crystal. A variation of this circuit is shown in Fig. 31. The resonant circuit has been moved to the collector and converted to a low-impedance series-resonant arrangement. In this oscillator it is also necessary to insert a high resistance in the base lead and to alter the emitter d-c biasing voltage to take into account the large voltage drop which develops across this resistor.
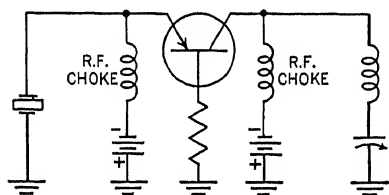
FIG. 31. A crystal-controlled oscillator with the crystal connected to the emitter and a series-resonant circuit connected to the collector.
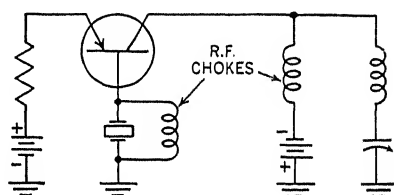
FIG. 32. A crystal-controlled oscillator with the crystal in the base circuit.

In Fig. 32 the crystal is connected to the base and bypassed by an r-f choke in order to maintain a d-c path between base and ground. A series-resonant circuit is connected between collector and ground and tuned approximately to the crystal frequency. If desired, the same results can be obtained by connecting the series-resonant circuit between emitter and ground.

In this chapter we covered a few of the more representative applications of point-contact and junction transistors in oscillatory circuits. Many additional combinations exist, but if the reader keeps in mind the characteristics of these transistors and the requirements of an oscillatory circuit, he should encounter little difficulty in understanding how these other systems function.

Mention should be made again, as it is in many places throughout the book, that transistors are highly temperature sensitive. It may well be that a circuit which is designed in conformity to transistor prin-

ciples will be found to be critical, unstable, or unreliable in actual application because due safeguards were not taken against the effects of temperature changes. In this chapter we have been primarily concerned with the basic operation of oscillators, and such stabilizing devices as emitter resistors were frequently omitted. This should not prove confusing in the least when they are encountered in actual circuits, since they will not alter basic operation.

QUESTIONS

1. How are oscillations normally produced in most vacuum-tube and transistor oscillators?

2. Draw the circuit of a simple vacuum-tube oscillator, and then show its transistor counterpart.

3. Draw the circuit of a transistor multivibrator.

4. Explain in detail how the foregoing multivibrator circuit operates.

5. Explain the purpose of each component in Fig. 12.

6. Why is the collector of the transistor in Fig. 13 tapped down on coil L_1? Explain the purpose of C_6 and C_7 in the same circuit.

7. Draw the diagram of a simple crystal junction-transistor oscillator.

8. How does the oscillator of Fig. 22 function?

9. Under what conditions will a point-contact transistor exhibit negative resistance?

10. Illustrate how the foregoing conditions are utilized in actual oscillatory circuits.

11. Why is a negative rather than a positive d-c voltage applied to the emitter of the transistor in Fig. 25?

12. Draw the diagram of a crystal oscillator using a point-contact transistor.

CHAPTER 6

TRANSISTOR RADIO RECEIVERS

Among the first commercial uses to which transistors were put were in small, portable radio-broadcast receivers. This is a natural application, since transistors lend themselves readily to compact, lightweight assemblies of the type required in such receivers. The portability feature is further enhanced by the fact that only small B-type batteries are required for power. Filament heating batteries, which vacuum tubes require and which occupy considerable space, are completely dispensed with here.

THE REGENCY RADIO RECEIVER

The first transistorized portable radio receiver to appear commercially was the Regency model TR-1, and it took advantage of every space-saving feature afforded the transistors and associated miniature components (see Figs. 1 and 2). Over-all dimensions of the unit are 5 by 3 by 1¼ in., enabling the entire set to fit easily into the pocket of a man's jacket. Weight of the set, with the batteries, is only 12 oz.

The schematic diagram of this receiver is shown in Fig. 3. There are four transistors and five stages. The extra stage is the second detector, and its function is performed by a germanium diode, here either a Raytheon CK706A or a Tungsol TS117. The transistors are of the NPN variety, and three special designs are used for the converter, i-f, and audio stages. Manufacturer of these units is Texas Instruments, Incorporated.

The first stage, containing transistor V_1, is essentially a self–oscillating converter. The input signal is picked up by a tuned ferrite-core coil which possesses a high Q. A low-impedance winding on the antenna coil couples the signal to the base of V_1.

Local oscillations are generated by a parallel-resonant circuit in the emitter circuit which is inductively coupled to a coil in the collector circuit. The low-impedance emitter is tapped down on the tuned cir-

FIG. 1. The Regency model TR-1 transistor radio is small enough to fit in the pocket of a man's jacket. (*Courtesy Regency.*)

cuit in order to provide the proper impedance match without lowering the Q of the circuit.

The foregoing oscillator arrangement is a fairly common one. Its equivalent vacuum-tube circuit is shown in Fig. 4. With the incoming signal and the local oscillator voltage both being applied to the converter transistor, the appropriate i-f signal is formed and then fed to transformer T_1 and the i-f stages beyond.

A 10,000-ohm resistor is placed in the emitter circuit to provide d-c stabilization against temperature changes and variations among different replacement transistors. The positive voltage which the emitter current develops across R_2 is counterbalanced by a positive voltage fed to the base from the battery. The actual voltage difference between these two elements is on the order of approximately only 0.1 volt.

The proper biasing voltage for the collector of V_1 is obtained from a 2,200-ohm resistor which is tied to the 22½-volt B+ line. A 0.001-μf
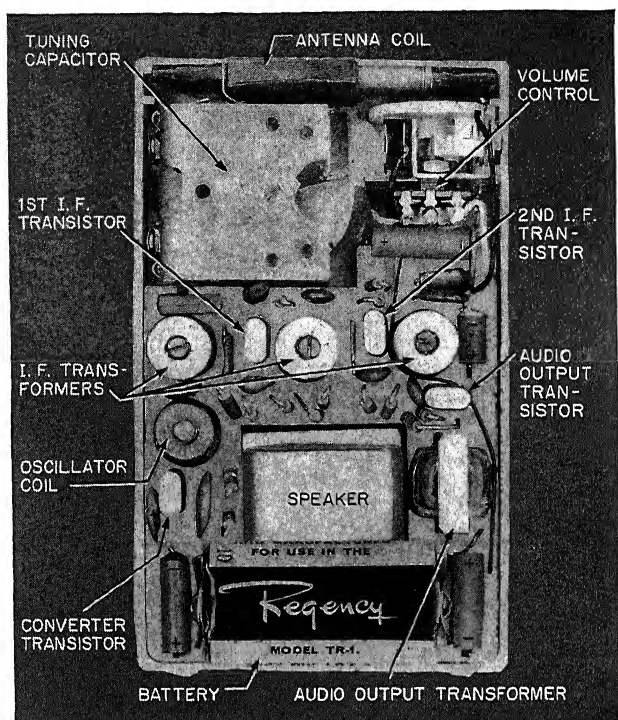
Fig. 2. Inside view of Regency model TR-1 transistor receiver showing layout of components. (*Courtesy Regency.*)

bypass capacitor C_7 keeps the signal currents out of the d-c distribution system.

There are two stages in the i-f system, and both operate at 262 kc. This frequency is considerably below the 465 kc common in vacuum-tube radio receivers, and it possesses the disadvantage of making this receiver more susceptible to image frequency pickup. However, the lowered frequency of operation is advantageous in that it provides greater gain and more stability.

The primary of each i-f transformer is tuned with a fixed capacitor, while the secondary is untuned. This is done to match the high collector impedance of the preceding stage to the low input impedance of the following stage. Peaking of each i-f coil is achieved by varying the position of an iron-core slug.

Each i-f stage is neutralized by feeding back a voltage from the base of the following stage to the base of the preceding stage. The feedback occurs through a 560-ohm resistor and a 100- to 200-$\mu\mu$f series

FIG. 3. The schematic diagram of the Regency model TR-1 receiver (*Courtesy Howard W. Sams & Co., Inc.*)

VOLTAGES MEASURED WITH NO SIGNAL INPUT
ALL MEASUREMENTS MADE WITH VTVM

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capacitor. The capacitor value is not specifically indicated, because its exact figure will depend upon the internal capacitance of the transistor and this may vary from unit to unit. Actually, what happens in this particular receiver is that whenever a replacement i-f transistor is ordered from the set manufacturer, a suitable neutralizing capacitor is
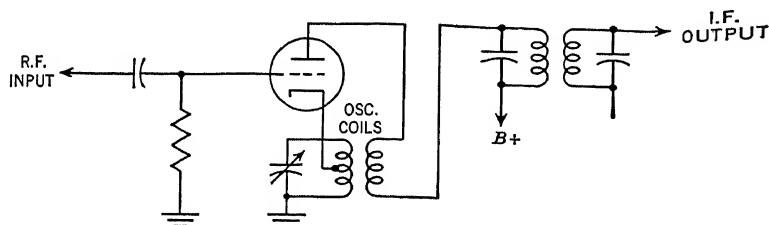
FIG. 4. The equivalent vacuum-tube circuit of the converter stage shown in Fig. 3.

sent along too, and both components must be replaced. Whether or not an i-f stage will require neutralization depends upon the collector-to-base capacitance of the transistor being used. In special high-frequency transistors, this internal capacitance may be small enough so that the neutralization may not be needed, especially at the lower radio or intermediate frequencies as in a receiver to be described. However, where this capacitance is large enough to cause noticeable feedback, neutralization, as shown in Fig. 3, must be used.

Automatic gain control is applied to the first i-f stage only. A negative voltage is obtained from the second detector and applied to the base of V_2. Its purpose is to regulate the emitter and collector currents and, with this, the stage gain. When the incoming signal becomes stronger, the negative a-g-c voltage rises, reducing the collector current of V_2 and, with it, the gain. The opposite condition prevails when the signal level decreases. This method is quite effective and provides a wide range of control. (A detailed discussion of automatic gain control in transistor receivers will be given after this analysis of the Regency model TR-1.)

The base bias for the second i-f stage is obtained from the emitter of the audio output stage (which here operates class A). This bias voltage is heavily bypassed by C_{21} and then further bypassed by C_{13}, a 0.05-μf capacitor.

Both emitters have d-c stabilizing resistors. (If it were not for the presence of C_8, C_{11}, C_{13}, and C_{15}, signal degeneration would occur also. As it is, only the direct portion of the current passes through R_5

and R_8.) Note, however, that the emitter resistor of the first i-f stage is only 560 ohms in value whereas the emitter resistor of the second stage is 2,700 ohms. The reason for this difference stems from the compromise that must be reached in the first i-f stage between good a-g-c action and the d-c stability of the amplifier. A value of R_5 greater than 560 ohms is desirable for stability purposes, but the degeneration that produces the stability would result in reduced gain-control action.

Each of the collectors of V_2 and V_3 receive their operating voltages through 2,200-ohm dropping resistors. C_{11} and C_{15}, at the top end of the resistors, serve as decoupling and bypass capacitors.

Following the second i-f stage is the second detector, and this function is performed by a germanium diode. The load resistor for the detector is the volume control. Note the impedance of the control, 1,000 ohms; this low value is needed to match the input impedance of the audio output stage V_5.

The final amplifier is operated with the emitter grounded through a 1,000-ohm resistor. Base bias is obtained from the voltage-divider network formed by R_{13} and R_{14}. The output transformer matches the 10,000-ohm collector impedance of V_5 to the low voice-coil impedance of the miniature speaker. Diameter of the speaker is only 2¾ in. Provision also exists for a small earphone plug which can be inserted into a small jack on the side of the receiver. When the earphone is in use, the speaker is disconnected.

The total power for the receiver is furnished by a hearing-aid type of 22½-volt battery. Total current drain is on the order of 4 ma.

The compactness of this receiver can be seen by an inspection of Fig. 2. All components, including the two-gang tuning capacitor and the speaker, are miniaturized. Operating voltage on electrolytic capacitors, C_9, C_{21}, and C_{19} is 3 volts; on C_{17}, it is 25 volts.

AUTOMATIC GAIN CONTROL OF TRANSISTOR AMPLIFIERS

The two most effective methods of controlling the gain of a transistor amplifier are varying the emitter current and varying the collector voltage. Figures 5 and 6 illustrate the variation in gain that can be achieved by both approaches.* Now to provide this control, a certain amount of d-c power is necessary. This arises from the fact that to do either of

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* Chow and Stern, Automatic Gain Control of Transistor Amplifiers, *IRE Trans. on Broadcast and Television Receivers,* vol. BTR-1, no. 2, April, 1955. No mention is made in the above discussion of the changes in transistor input and output impedances accompanying changes in emitter current flow. These do occur, and they also contribute to the changes in gain.
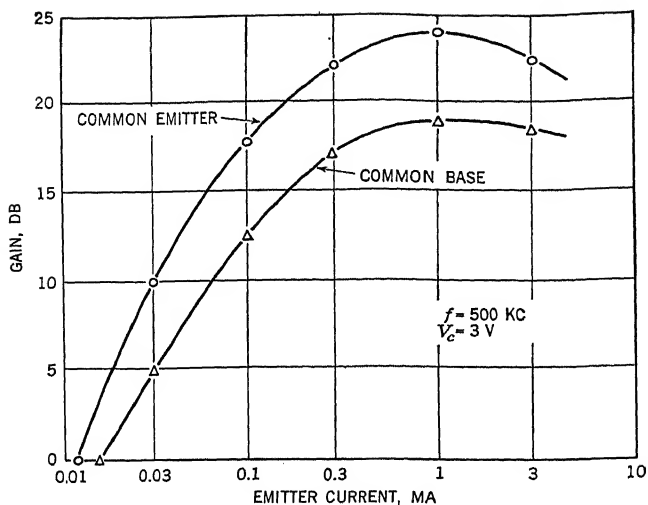
FIG. 5. Transistor amplifier gain as a function of the emitter current. The effect is shown for common-emitter and common-base amplifiers.
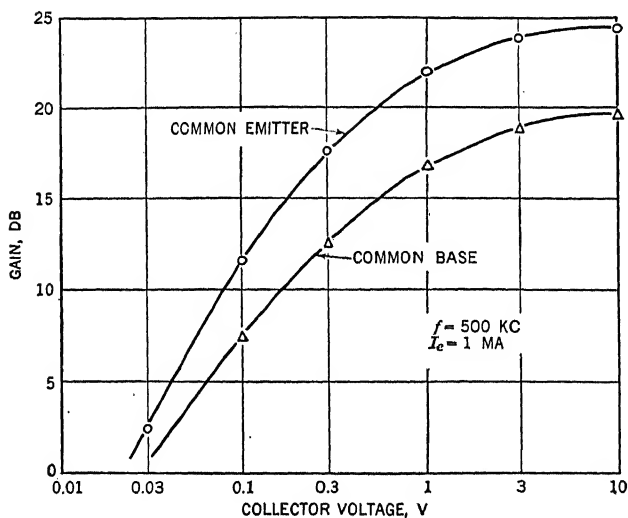
FIG. 6. Transistor amplifier gain as a function of the collector voltage. The effect is shown for common-emitter and common-base amplifiers. To be effective, the control voltage (or current) must be capable of reducing the collector voltage to low values.

these two things requires current from the control source. In vacuum-tube amplifiers, little or no power is required because the control voltage is fed to the grid of a tube and this element, being negative with respect to the cathode, draws no current. A transistor, on the other hand, is a current-operated device, and to alter its current, we must have the control stage supply a suitable amount of its own current. This, in turn, means that power must be expended.

The control voltage is obtained almost invariably from the second detector; hence, this is the stage which must supply the control power. To assist the detector in this task, the controlled transistor i-f amplifier is usually made to function as a d-c amplifier for the control signal. For example, in the stage shown in Fig. 7, the emitter current is a-g-c con-
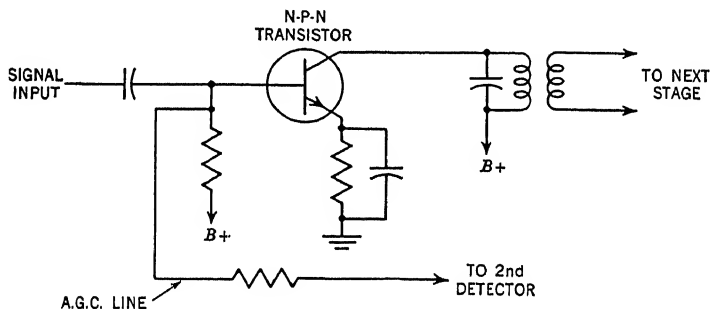
FIG. 7. An example of I_e control of an i-f amplifier. The a-g-c voltage is applied to the base.

trolled. However, instead of varying the emitter current directly, the control voltage is applied to the base of the transistor, and the resulting changes in direct base current are amplified and appear as larger changes of emitter current. When the incoming signal is strong, then a voltage is fed back which serves to reduce the emitter current, and the stage gain is reduced. Conversely, when the incoming signal is weak, the voltage fed back is reduced in value, permitting more emitter current to flow and raising the gain.

By reducing the emitter current, we also reduce the collector current and, hence, the strength of the signal developed across the output tuned circuit.

If sufficient power is available in the detector circuit, an attempt can be made to control the emitter current directly by introducing the control voltage in the emitter circuit of the i-f stage. However, in the absence of this power, the control voltage can be applied to the base of the i-f stage, as shown.

The graph of Fig. 6 also demonstrates that the gain of a transistor may be varied by changing the collector voltage. A circuit designed to achieve this is shown in Fig. 8. Note the presence of the resistor in the
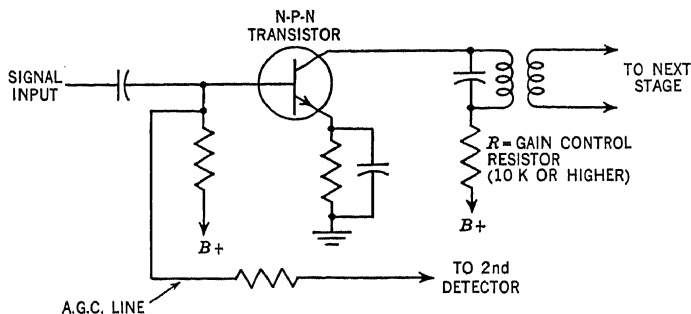
FIG. 8. An example of V_c control of an i-f amplifier. The a-g-c voltage is applied to the base. Note the presence of a fairly high-valued resistor in the collector lead.

collector lead. The control voltage is again applied to the base, and variations in base current appear as amplified variations of emitter and collector current. The resulting change in voltage across the resistor in the collecting circuit also leads to changes in collector voltage and gain.

In order to effect control by this method, then, a resistor is needed in the collector circuit. There is, however, an even more significant difference between this system and the prior one. This concerns the polarity of the control voltage applied to the base of the controlled i-f amplifier. In the previous method, the a-g-c voltage served to *reduce* base and emitter currents when the incoming signal increased in amplitude. In an NPN transistor, this is achieved by making the base less positive than before. For a PNP transistor, the control voltage would have to make the base more positive. In the V_c control method, we follow the reverse practice. Now the a-g-c voltage tends to *increase* the base and emitter (and collector) currents with increasing signal strength. This causes the voltage drop across the collector resistor to rise, reducing V_c and, with it, the gain of the stage. (For the V_c control method, an NPN transistor would require a positive-going voltage when the signal increased in strength. Conversely, a PNP transistor would require a negative-going voltage under the same conditions.)

The object, in this method, is to control transistor gain by varying the collector voltage. To reduce the gain, we must reduce the collector voltage; on the other hand, to increase the gain, we raise the collector

voltage. To achieve effective control, the collector resistor should have a value in the vicinity of 10,000 ohms or more. Too small a resistance value will not provide the desired range of control, while too high a resistance will lead to premature cutoff and distortion.

The best guide for the service technician to follow in attempting to identify the system of control is to determine what happens to the emitter current as the signal level rises. If the control voltage increases the emitter current with increasing signal level, then V_c control is being employed. Under these circumstances, a collector resistor will be found. But if the control voltage depresses the emitter current with signal level increase, than I_e control is being employed. A collector resistor may or may not be used, but even if it is, it does not directly enter into control of the amplifier gain, because it does not reduce the collector voltage to the point where gain is affected. In transistors, collector current is independent of collector voltage above a certain minimum value. In I_e control we stay above this minimum; in V_c control we go below it.

In the receiver shown in Fig. 3, I_e control is being employed; i.e., the a-g-c voltage becomes increasingly negative with rising signal, and this voltage, fed to the base of an NPN transistor, *reduces* the emitter current. The 2,200-ohm collector resistor is low enough in value not to affect collector current or transistor gain seriously.

An i-f system employing V_c-type control is shown in Fig. 9. NPN transistors are employed in the two i-f stages as well as in the detector. The detector, which we shall discuss presently in greater detail, is operated essentially in class B, so that it is biased close to cutoff. The
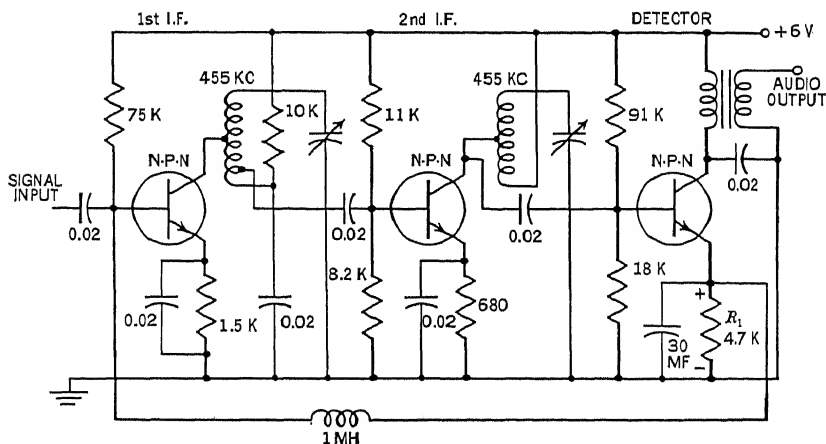
Fig. 9. Two-stage i-f amplifier followed by detector with V_c-type a-g-c control.

voltage drop across R_1 is such that the top end is positive with respect to the bottom end. When the average level of the signal rises, the voltage across R_1 increases too. This voltage, which is well filtered by a 30-μf capacitor so that the only variations are those due to slow changes in signal level, is fed back through a 1-mh choke to the base of the first i-f amplifier. Since the transistor here is of the NPN variety, a positive rise in voltage will cause the base, emitter, and collector currents to rise. This, in turn, will increase the voltage drop across the 10,000-ohm collector resistor and reduce the collector voltage. The second i-f stage is not controlled.

Another V_c-controlled amplifier is shown in Fig. 10. Here the collector voltage is controlled directly because it is obtained from the
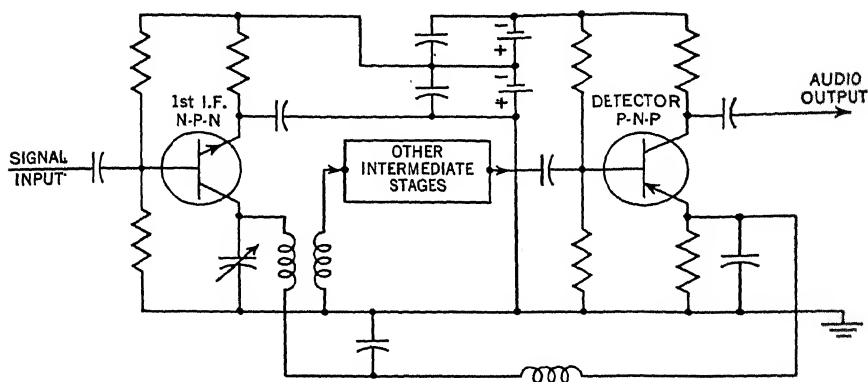
FIG. 10. Another V_c-controlled system. Here the collector voltage of the first i-f stage is controlled directly because it is obtained from the emitter resistor of the second detector.

emitter resistor of the second detector. The latter resistor is heavily bypassed so that only the d-c changes in voltage across it affect the collector of the i-f stage.

The 1-mh choke of Fig. 9 is to prevent shorting out the incoming signal reaching the i-f stage. In Fig. 10, the same choke is more in the nature of a filter to prevent the i-f signal from reaching the detector from the collector of the first i-f amplifier.

A SECOND TRANSISTOR RECEIVER

Another radio receiver, which is designed along somewhat similar lines as the Regency set but which contains a greater number of stages, is shown in Fig. 11. The line-up of stages includes a converter, three i-f
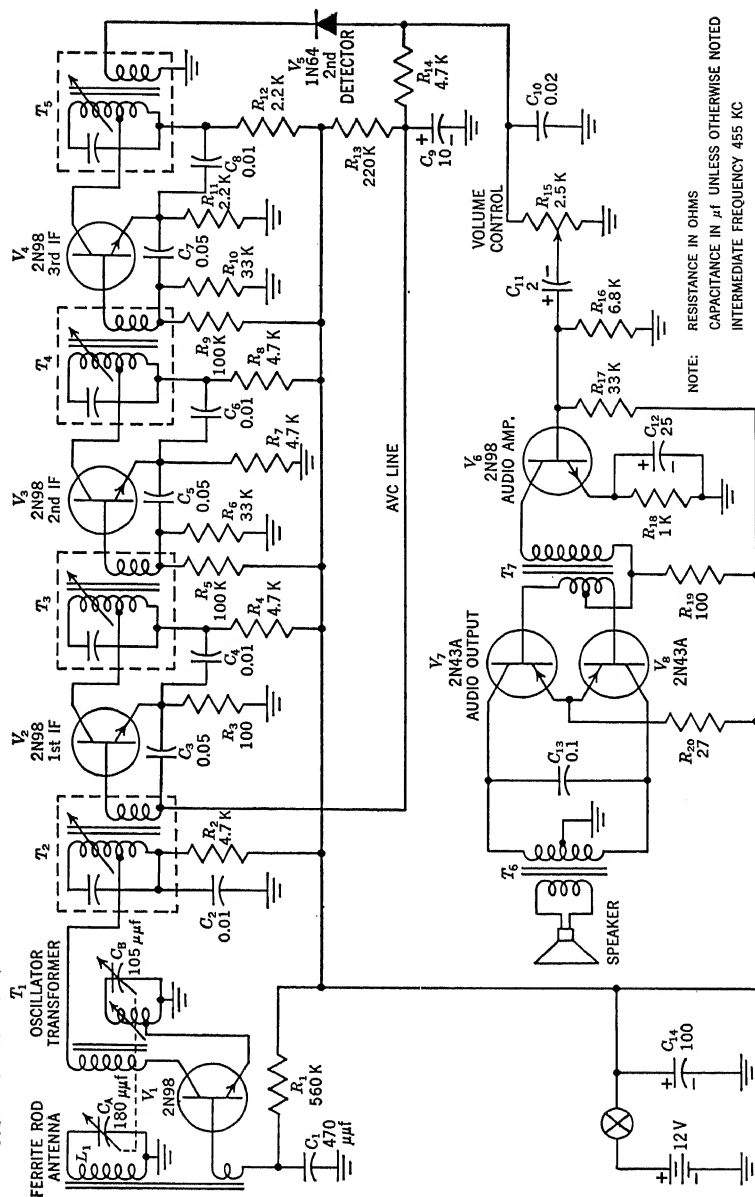
FIG. 11. A transistorized portable radio receiver designed along lines similar to the previous Regency receiver.

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amplifiers, a germanium diode detector, and two audio amplifiers. The maximum power output is 115 mw, which is more than ample for this particular purpose. The B+ voltage is 12 volts, and the current drain, at low levels, is 5 ma. At high peak levels it may go as high as 20 ma. A pair of Eveready W-456-type batteries could be expected to have a life in excess of 500 hr if used at the rate of 2 hr a day.

The transistors used in the converter, i-f, and first a-f stages are all 2N98's. This is an NPN type of transistor. In the output stage, 2N43A transistors are employed. These are PNP units.

The converter stage is closely similar to the same stage in the previous receiver. In order to intercept as much signal as possible, the ferrite rod on which the antenna coil L_1 is wound is ⅜ in. in diameter and 8 in. long. The main winding on the antenna coil contains 90 turns and is tuned by a 180-$\mu\mu$f variable capacitor. Tuning range extends from 535 to 1,650 kc. A smaller, six-turn secondary winding then transfers the signal from the primary to the base of the converter transistor V_1.

The oscillator transformer T_1 is connected between collector and emitter of V_1. The emitter is tapped up 13 turns on the 130-turn tuned secondary winding. The primary of the oscillator transformer is untuned, connecting to the collector at one end and the input i-f transformer T_2 at the other end. The intermediate frequency produced in V_1 is 455 kc.

R_2 and C_2 form the collector decoupling filter, with R_2 chosen to limit the collector dissipation to a safe value in case the oscillator portion of this stage should cease to function. R_1 brings the d-c voltage to the base of V_1, and its value is so selected that the collector current is between 0.5 and 1.0 ma.

There are three stages of intermediate frequency, with an over-all gain of approximately 20 db per stage. Each transistor is connected with the emitter grounded. The same interstage transformer is used throughout, and in each only the primary is tuned. The collector is tapped down on the primary winding to a point where its 10,000 ohms is matched. The secondary of each transformer is untuned in order to match the 500-ohm input impedance of the following stage. The only variation among transformers occurs in T_5, where the secondary impedance is altered to match the loading of the diode detector.

Automatic-gain-control bias is applied to the base of only the first i-f amplifier. A negative voltage is obtained from the diode detector and fed back to the base of the first i-f transistor. Note that this a-g-c voltage is applied in series with a positive d-c voltage (through R_{13}), and it is the latter which establishes the bias on the first i-f transistor base

when no signal is being received. When a signal is received, the a-g-c voltage reduces the positive biasing voltage by an amount dependent upon signal intensity. The method of control here is I_e.

The same i-f stage also has a small stabilizing resistor in the emitter lead. Its value is lower than the corresponding resistors in the emitter leads of the other i-f stages, and the reason for this was discussed previously. Base bias for the other i-f transistor amplifiers is provided in each instance by a voltage divider.

The detector is a germanium diode (1N64 or equivalent) with the 2,500-ohm volume control as its d-c load. A 0.02-μf capacitor C_{10} acts as an i-f bypass. Automatic-gain-control bias is fed through the combination of R_{14} and C_9.

The audio voltage developed across the volume control is applied to the base of the first audio amplifier. R_{17} and R_{16} form a voltage divider to provide the proper base voltage for this transistor. A 1,000-ohm stabilizing resistor is employed in the emitter lead, but it is shunted with a 25-μf capacitor to prevent signal degeneration.

The output stage is a common-emitter push-pull class B amplifier. To reduce the crossover distortion, a small amount of forward bias is used. This voltage is obtained from R_{19}, a 100-ohm resistor located in the collector circuit of the previous audio-amplifier stage. This bias source makes it unnecessary to add an additional bleeder across the battery supply. Some stabilization and degeneration are produced by the 27-ohm resistor R_{20} in the common emitter return. The audio-frequency response is limited by C_{13}, the 0.1-μf capacitor across the output transformer.

The two 2N43A transistors are PNP units, and this is the reason the center tap of the output transformer primary is grounded. This connection makes the collector negative with respect to the base of each unit.

An interesting feature of this receiver is the lack of neutralizing capacitors in the i-f stages. 2N98 transistors are specifically designed for higher frequency application, and the relatively small collector-base feedback capacitance permits these units to be used at the 455-kc intermediate frequency without neutralization.

RAYTHEON TRANSISTOR RADIO

The schematic diagram of another transistor portable radio is shown in Fig. 12. This circuit contains a separate mixer and oscillator, two i-f stages, a transistor second detector, an audio amplifier, and a class B push-pull output. Direct-current power is supplied by four 1½-volt
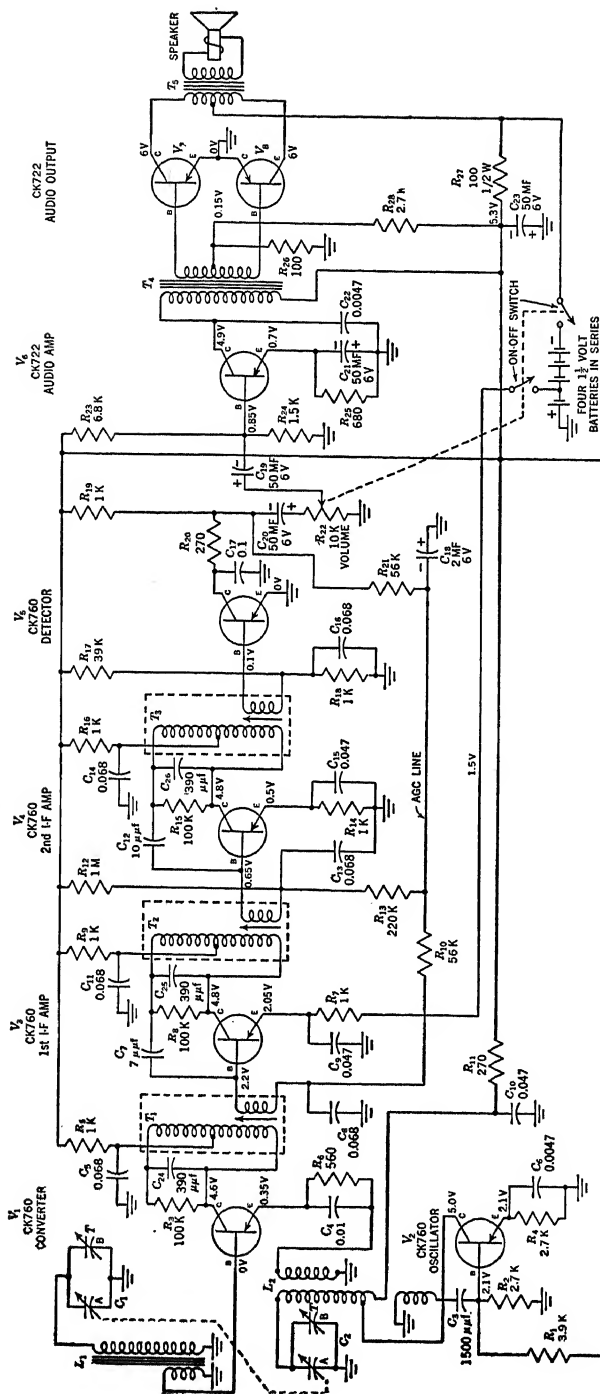
Fig. 12. Schematic diagram of one of Raytheon's portable transistor receivers. (*Courtesy Raytheon Mfg. Co.*)

NOTE: UNLESS OTHERWISE SHOWN, RESISTOR VALUES ARE IN OHMS AND ARE 1/3 WATT
CAPACITOR VALUES ARE IN MICROFARADS UNLESS OTHERWISE SHOWN
DC VOLTAGE READINGS TAKEN UNDER NO SIGNAL CONDITIONS WITH BATTERY VOLTAGE
−6VDC. VOLTAGES AT TRANSISTOR SOCKETS WILL VARY SLIGHTLY WITH TRANSISTOR
CHANGES
USE ONLY VTVM

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flashlight batteries, and the audio power output is in the vicinity of 100 mw.

The mixer-oscillator stage (with minor modifications) was discussed in Chap. 5. The feedback of energy from the collector of V_2 to the base is accomplished by means of the small tickler coil that is connected to the 1,500-$\mu\mu$f base capacitor. The collector itself is tapped down on L_2 so that an impedance match can be secured, while, at the same time, the Q of the coil is not loaded down to the point where frequency stability and tracking are affected.

The oscillator output is inductively coupled to the secondary of L_2 and then transferred via C_4 to the emitter of the mixer stage. The 560-ohm resistor paralleling C_4 serves to stabilize V_1. The mixer combines the oscillator voltage with the incoming signal, received via the base, and the resultant i-f signal appears in the collector circuit and is transferred via T_1 to the first i-f amplifier. R_5 and C_5 form a decoupling filter to prevent the signal from reaching the B— line, with R_5 chosen to limit the collector dissipation to a safe value should the oscillator fail to function properly.

The two i-f stages employ grounded-emitter arrangements, and both stages are a-g-c controlled. The a-g-c voltage is obtained from a class B power detector and applied to each base. Since these are PNP transistors, the base should be negative with respect to the emitter. A negative voltage is supplied to each base from the d-c battery line. To vary the gain of each stage, the output voltage from the detector becomes more positive as the incoming signal level increases. This has the effect of reducing the bias between the base and emitter and, in essence, lowers the emitter and collector currents through the transistor. As the current decreases, the gain of the stage drops. In short, I_c control is employed.

In the first i-f stage, the bottom end of the emitter resistor R_7 connects to the —1.5-volt terminal on the battery. An additional —0.55 volt develops across the 1,000-ohm emitter resistor, so that the total emitter voltage with respect to ground is —2.05 volts. The voltage of the base is 2.2 volts, and this is obtained through the a-g-c line and the connection of this line to R_{10}. The latter resistor ties in, at its opposite end, to the 5.3-volt line from the battery. The net bias, then, between base and emitter is 0.15 volt with the base more negative than the emitter. When the a-g-c bias is active, upon the arrival of a signal, it will act to reduce the bias difference between base and emitter.

The collector of the first i-f stage receives its bias voltage via R_9. Voltage of the collector is —4.8 volts with respect to chassis. (The negative signal in front of the various voltages in Fig. 12 has been

omitted, but the fact that each should be preceded by a negative sign is quite evident.)

In the second i-f stage, the actual base and emitter voltage values are different, but it will be noted that the base-to-emitter voltage remains the same.

The reason for returning the emitter of V_3 to a negative tap on the battery is that it permits the gain of this stage to be reduced sufficiently to prevent overload of the second i-f or the detector. In the second i-f stage, the emitter resistor is returned to ground, and because of this, the a-g-c voltage cannot reduce the transistor current to so small a value as it can in the first stage.

The intermediate frequency is 455 kc. C_7 (7 $\mu\mu$f) and C_{12} (10 $\mu\mu$f) are neutralizing capacitors.

The stage following the second i-f is the second detector, and a CK760 transistor is employed here in a class B power detector arrangement. This type of detector was once fairly popular in vacuum-tube circuits, and a good deal of this popularity stemmed from the fact that it will amplify the signal. It is the latter advantage which accounts for its use here, and in its present application 10 db of gain is obtained. It would be simpler and cheaper to use a germanium diode, as in the two previous sets, but a diode introduces a loss, and gain here is important. In vacuum-tube receivers, the class B power detector is no longer used because sufficient prior amplification is available so that detector gain is not required, because diodes are cheaper, and because a vacuum-tube power detector introduces a considerable amount of distortion on relatively weak signals. In the transistor class B detector, less distortion is introduced because transistor characteristic curves are considerably more linear than vacuum-tube characteristic curves. As a matter of fact, transistors will give essentially linear detection at smaller power levels than even diodes.

Not to be overlooked also is the ability of a transistor detector to supply more a-g-c power than a diode detector.

For those readers who may not be familiar with power detectors, the following explanation is given. The E_G-I_P characteristic curve for a triode is given in Fig. 13, and if we bias the tube close to the cutoff point, then the incoming signal applied to the grid will vary back and forth about this point. However, the negative half of the input signal will operate over the curved portion of the characteristic, producing considerably less plate current than the positive half cycles of signal. (Portions of the negative half of the signal will drive the tube to cutoff.) Essentially we have rectified (i.e., detected) the signal, and if we remove the i-f component, we shall obtain the desired audio intelligence.

In the transistor detector of Fig. 12, the emitter is connected directly to ground. The potential of the base is established by the divider network of R_{17} and R_{18}, and this voltage is so low that the stage is close to cutoff. Under no-signal conditions, the collector voltage is very close to the full B— voltage. The a-g-c line connects also to the collector of V_5, and it is through this connection that the base elements of V_3 and V_4 receive their operating voltages.
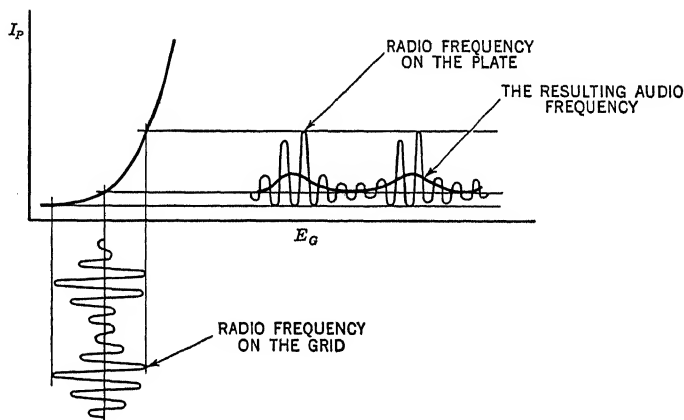
FIG. 13. The manner in which a class B power detector operates.

When a signal is received, the collector current of the detector increases, and since this is a PNP transistor, electron flow will be from the battery to the collector. This will produce a voltage drop across R_{19} such that the collector will become *less* negative or *more* positive. This change will be transmitted to the bases of the controlled i-f amplifiers and result in a current decrease through these transistors. In this way the gain of the two i-f stages is controlled. R_{21}, R_{13}, R_{10}, C_{18}, C_{13}, and C_8 serve to filter out any audio components of the a-g-c voltage and to establish the time constant of this network.

The remainder of this receiver circuit is fairly straightforward and will present little difficulty to the reader. The signal from the detector appears across the volume control R_{22} and is taken from here and applied to the base of V_6, the audio amplifier. R_{23} and R_{24} form a voltage-divider network to provide the desired bias for the stage. A stabilizing resistor is present in the emitter circuit, and this is suitably bypassed by a 50-μf capacitor. The 0.0047-μf capacitor from collector to ground serves to remove any stray i-f voltage that may have reached this point.

The final stage is a class B push-pull output amplifier. The full 6

volts is applied to the collector elements to obtain the desired power output. A small base-to-emitter bias is used to minimize crossover distortion and to make it easier to substitute other CK722 transistors should replacement become necessary. The no-signal current for the push-pull amplifier is about 1 ma plus 1.8 ma in the bias bleeder. At maximum rated output, the current drain of this stage is about 28 ma.

Layout of the various components in this receiver is shown in Fig. 14. The CK760 transistor which is employed in the r-f, i-f, and detector stages appears in Fig. 15.

Fig. 14. A rear view of the Raytheon portable transistor receiver whose diagram appears in Fig. 12. (*Courtesy Raytheon Mfg. Co.*)

In another model developed by Raytheon, a somewhat modified arrangement was employed (see **Fig. 16**). There is only one i-f stage, and a germanium diode serves as the second detector. However, following the second detector there are two audio amplifiers and a class B push-pull output stage. The designers evidently felt that more could be gained by replacing one i-f stage by an additional audio amplifier.

Note, too, that transformer coupling is employed throughout the entire audio system, including that between the detector and the first audio amplifier. This, too, is designed to enhance the over-all gain.

The a-g-c voltage in this receiver is applied to the mixer rather than

the i-f amplifier. When questioned about this, Raytheon engineers indicated that better over-all control action could be obtained with this approach than if the a-g-c voltage had been applied to the i-f stage.
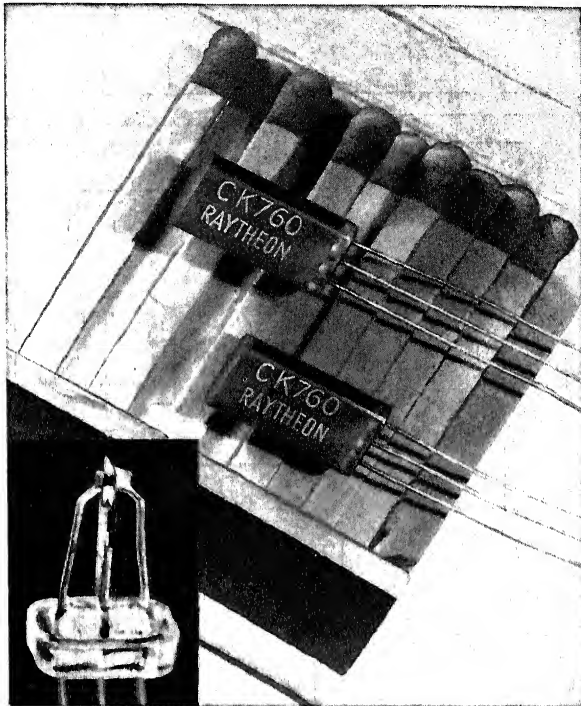
Fig. 15. The CK760 transistors which Raytheon employs in its portable receiver. These units are manufactured by Raytheon. The inset in the photograph shows the internal structure of this transistor. (*Courtesy Raytheon Mfg. Co.*)

However, it is necessary with this method to employ a separate oscillator; in a combined converter, a change in a-g-c bias would cause the oscillator frequency to shift.

TRANSISTOR AUTOMOBILE RADIO

The low-voltage requirements of transistors make their application in automobile receivers particularly desirable, since they can operate directly from the 6- or 12-volt battery and thereby eliminate the need for a vibrator, a power transformer, and a rectifier. Not only will this result in a lowering of costs and a substantial savings in space requirements, but it will also help to reduce servicing expense. It has been
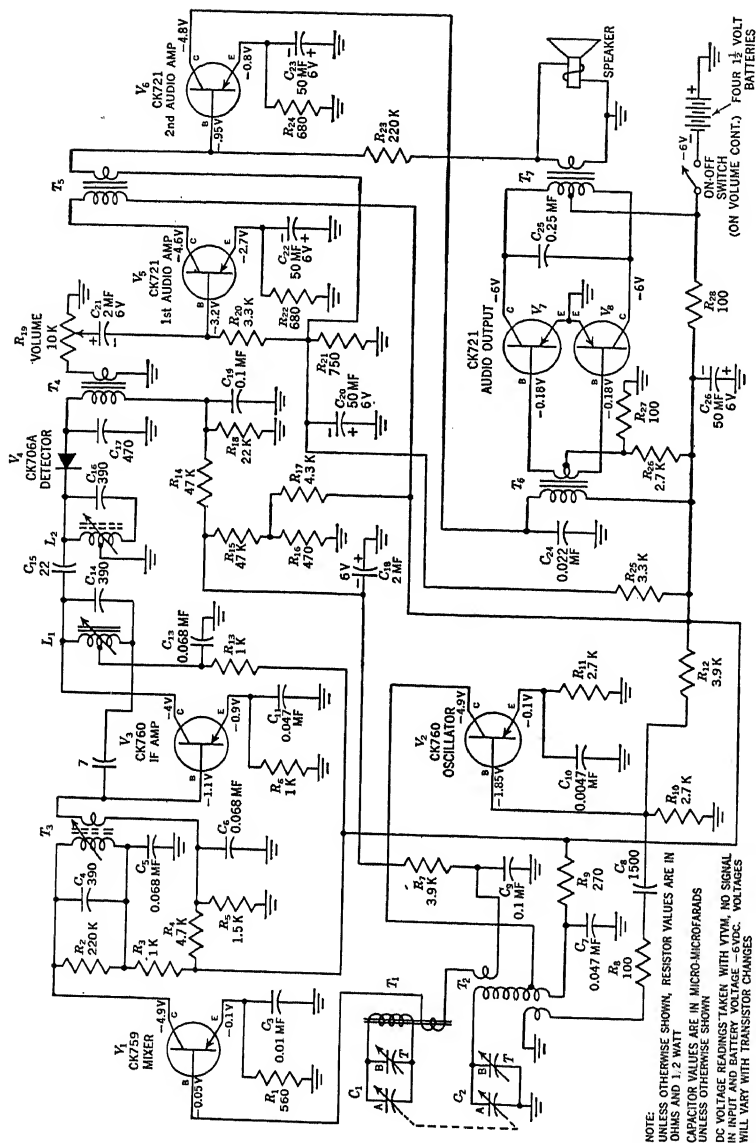
FIG. 16. Diagram of a later Raytheon portable transistor receiver. (*Courtesy Raytheon Mfg. Co.*)

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found that 85 per cent of the defects which occur in automobile radios stem from a breakdown of the vibrator, transformer, or rectifier. Eliminated, too, is vibrator hum. Finally, the drain on the car battery by the radio is lowered by a factor of 10.

The schematic diagram of a transistor automobile radio is shown in Fig. 17. In common with many such receivers, there is an r-f stage, a converter, two i-f amplifiers, a transistor detector, an audio amplifier, and a push-pull output stage. Power output is 2 watts, and the over-all receiver sensitivity is 2 μv. After we have investigated the circuit, the performance characteristics will be considered in somewhat greater detail.

The antenna for this receiver is a conventional automobile rod antenna, and this feeds the tuned primary of the antenna transformer T_1. The secondary of T_1 is untuned in order to match the low input impedance of V_1, the r-f amplifier. Tuning of the transformer is carried out by means of an adjustable powdered-iron tuning slug which is ganged to similar slugs in the mixer and oscillator coils. Each slug is 1.2 in. long by 0.18 in. in diameter; slug travel is about 1 in.

Bias for the base of V_1 is obtained at the junction of R_2 and R_3 and is on the order of -1.5 volts. The emitter contains a stabilizing resistor R_4 and a suitable r-f bypass capacitor C_4. Automatic-gain-control voltage from the second detector is applied to R_4 by resistor R_5. More on this in a moment.

The output signal of V_1 reaches the base of the following mixer by means of transformer T_2. The turns ratio of this transformer is such that the 10,000-ohm output impedance of V_1 is matched to the 500-ohm input impedance of the mixer. Transformer operating Q is on the order of 15 to 20. Owing to the step-down turns ratio necessitated by the impedance match, the transformer reduces the signal by 3.7 db. However, this is greatly overshadowed by the gain of the r-f stage, which is 20 db, and the conversion gain of the mixer, which is also 20 db.

It was noted in Chap. 4 that r-f amplifiers are frequently operated at less than full battery voltage in order to secure a better signal-to-noise ratio. This practice is followed here.

The oscillator V_3 possesses a tuned primary and an untuned secondary. A relatively high capacitance is shunted across the primary in order to improve the stability of the oscillator. Feedback of energy is between collector and base. Bias voltage for the base is obtained from the junction of R_2 and R_3 and is about -1.5 volts. The collector receives its operating voltage through R_9. The $R_{10}C_{11}$ network in the emitter circuit introduces degeneration in the oscillator circuit. However, this

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FIG. 17. Schematic diagram of a transistor automobile receiver. (*Courtesy RCA*)

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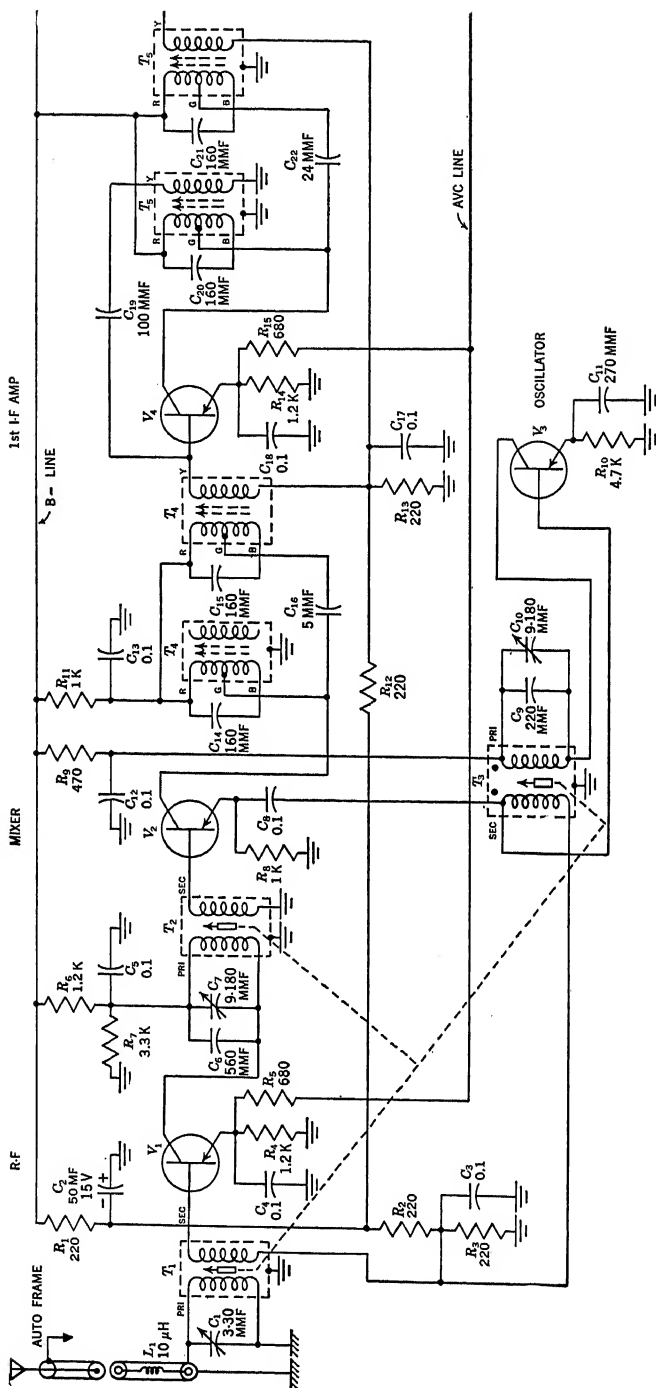
also reduces the loading of the oscillator-tuned circuit by the transistor input circuit and provides greater oscillator stability.

The oscillator voltage is injected into the mixer circuit by way of C_8 and R_8. Approximately 0.4 volt rms is used, this having been found to provide the highest conversion gain in the mixer. Too strong or too weak an oscillator injection voltage will result in less i-f signal being made available to the i-f system, and the audio output will be correspondingly affected. Here is a somewhat critical point in the receiver and one that should be inspected if weak volume is reported.

Coupling capacitor C_8 and the secondary of T_3 both present a low impedance at both radio and intermediate frequencies so that R_8 is effectively bypassed to ground for both input and output signals.

Three i-f interstage coupling networks are employed for the two i-f amplifiers, with each network consisting of two capacitively coupled double-tuned transformers T_4–T_4 and T_5–T_5 and a single-tuned transformer T_6. These provide the i-f response curve shown in Fig. 18; the
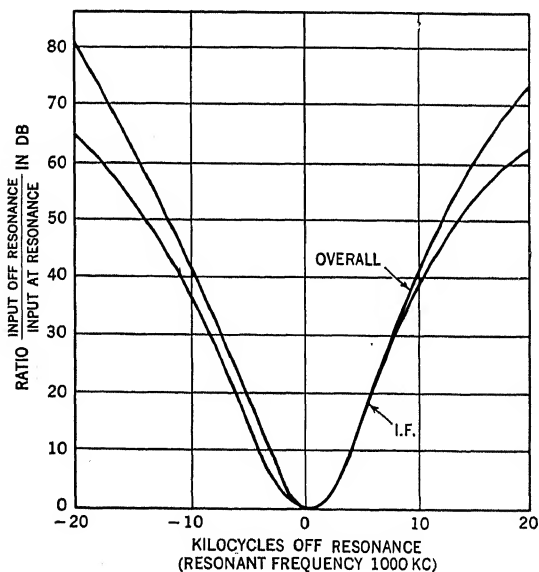
FIG. 18. The i-f and over-all selectivity curves of the receiver shown in Fig. 17. (*Courtesy RCA.*)

over-all response curve (radio and intermediate frequency) is also shown, and it can be seen that the over-all selectivity is determined almost entirely by the i-f coupling networks.

Biasing of the first i-f stage is similar to the r-f stage, with approx-

imately -1.5 volts being applied to the base from the junction of R_{12} and R_{13}. The emitter possesses a 1,200-ohm stabilizing resistor, and a 680-ohm resistor brings the a-g-c voltage into the stage. The collector of V_4 ties directly into the B— line. The second i-f stage also receives its base bias from the junction of R_{12} and R_{13}, but its emitter does not tie into the a-g-c line. However, the emitter does possess an 1,800-ohm stabilizing resistor and a 0.1-μf bypass capacitor to prevent signal degeneration. R_{16} and C_{23} form a decoupling filter for the collector of V_5.

Neutralization of the i-f stages is provided by C_{19} and C_{24}. An over-all gain of 50 db is obtained from the base of the first i-f amplifier V_4 to the base of the second detector V_6.

The second detector is operated as a class B power detector. Zero bias is employed between base and emitter, and very little direct emitter current flows in the detector under no-signal conditions. When a signal is received, current flows in the collector circuit of the detector, and this current, passing through the volume control, provides the audio signal for the following stages. C_{30} shunts the i-f components of the detected signal around the volume control and back to the emitter.

Whatever current flows in the collector circuit passes through R_{19}, with the emitter end of R_{19} becoming negative with respect to the ground end. This negative voltage, properly filtered to remove audio variations, is fed back to the emitters of the r-f and first i-f stages, providing automatic gain control. Since the voltage across R_{19} is negative (with respect to ground), an increase in signal strength will cause the value of this voltage to rise. This will drive the controlled emitters more negative than they were, in effect reducing the bias difference between each emitter and its base. This is equivalent to bringing each transistor closer to cutoff, reducing its current flow and, in consequence, its gain.

The reader will recognize that in this system we have direct I_e control of gain. In order to obtain sufficient power to effect this control, a transistor detector was needed.

The RC networks in the emitter circuits of the detector, the r-f amplifier, and the first i-f amplifier provide suitable filtering of the r-f and audio components of the a-g-c voltage. R_{18}, between the base and emitter of the detector, improves the linearity of the rectifying action.

The audio signal which is developed across the volume control is applied to the base of V_7, the audio amplifier. The design of this stage is straightforward, with R_{23} and R_{24} forming a voltage divider to provide V_7 with the proper base bias voltage. Control of the operating current of this amplifier is also provided by emitter resistor R_{25}. The

collector current of V_7 is approximately 15 ma at moderate temperatures; it increases to 30 ma at 80°C and drops to 10 ma at -40°C. C_{32} is an emitter bypass capacitor, being essentially in parallel with R_{25}.

The signal from V_7 is transformer-coupled to a class B push-pull output stage consisting of V_8 and V_9. For best results (i.e., minimum distortion), V_8 and V_9 should be selected with characteristics as nearly similar as possible. Both output transistors are connected with emitters grounded. Furthermore, a small base-to-emitter bias is employed to minimize nonlinearity in the crossover segment of the characteristic curves. There is an optimum value of threshold emitter current which results in the least amount of nonlinearity and the bias is chosen accordingly. However, while this value of current is independent of temperature, the corresponding base-to-emitter voltage needed to develop this current does vary with temperature, in this case approximately -0.0025 volt per °C. To develop the desired voltage variation with temperature automatically, two thermistors,* R_{29} and R_{33}, are inserted in the base-to-emitter bias path. The resistance of these thermistors will vary with temperature in such a way that the desired voltage variation is obtained and the emitter current is kept steady.

The resistance network consisting of R_{27} through R_{33} may appear to
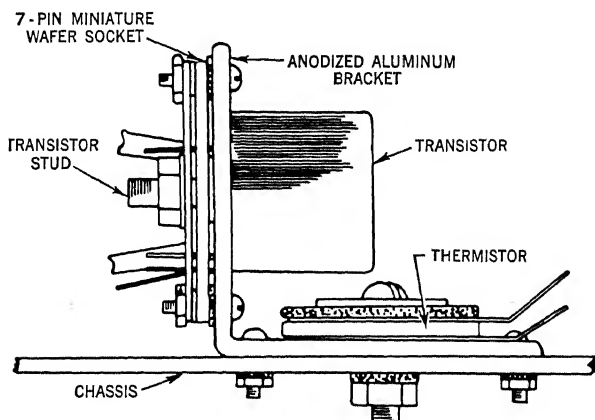
FIG. 19. Power transistor and thermistor mounting arrangement employed in receiver of Fig. 17. (*Courtesy RCA.*)

* A thermistor, for those readers not acquainted with it, is a thermally sensitive resistor which has a high negative temperature coefficient of resistance. That is, its resistance decreases as the temperature rises and increases as the temperature falls. In addition to their present application, thermistors are also employed for automatic volume compression and expansion, temperature control, and temperature and power measurements.

be somewhat complex, but its only purpose is that just indicated. Also, the transistor-thermistor mounting arrangement shown in Fig. 19 is employed to maintain close thermal contact between these components so that they will be at the same temperature. This is particularly significant; without it the effectiveness of this control circuit is reduced.

The speaker is coupled to the collectors of V_8 and V_9 through autotransformer T_8. This method was chosen because of the close coupling it provides, with resultant high transformer efficiency. Power gain of the output stage is on the order of 24 db.
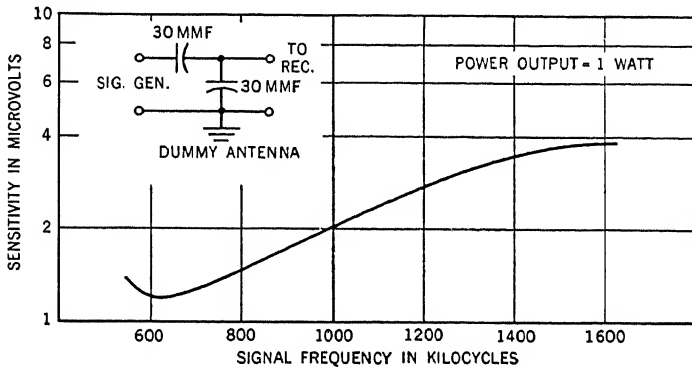
Fig. 20. Automobile-radio-receiver sensitivity as a function of signal frequency.

Capacitor C_{34} introduces negative feedback in the output stage for frequencies above 2 kc. This controls the extent of the high frequencies passed on to the speaker. C_{34} serves the same purpose as the common practice of shunting a capacitor across the primary winding of the output transformer.
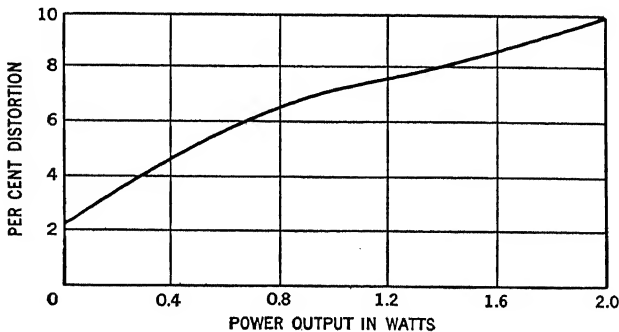
Fig. 21. Distortion versus power output for automobile receiver of Fig. 17. (*Courtesy RCA.*)
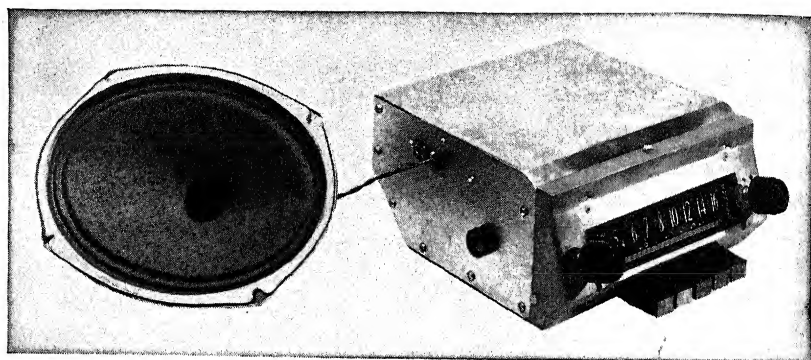
Fig. 22a. Outward appearance of the RCA developmental transistor automobile receiver. The reduced size of the receiver can be seen by comparison with the nearby speaker. (*Courtesy RCA.*)
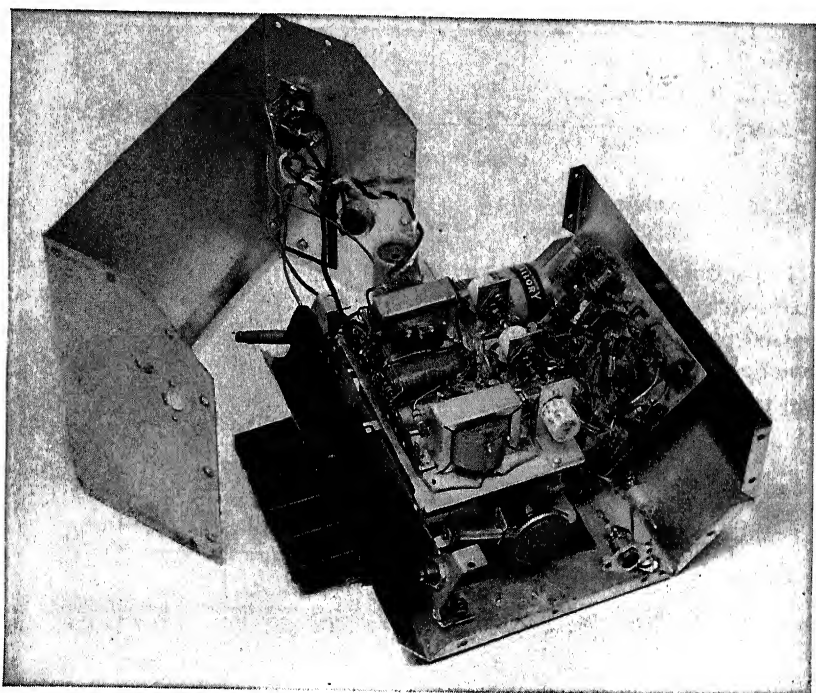
Fig. 22b. An internal view of the RCA developmental transistor automobile receiver. The two power transistors are seen in the foreground. (*Courtesy RCA.*)

Since this is an automobile radio, a number of precautions must be taken to eliminate interference from the car ignition system. A spark plate C_{36} and an r-f choke and capacitor L_2 and C_{35} prevent high-frequency interference signals from entering the radio via the battery line. Rejection of high-frequency impulse type of ignition interference appearing on the antenna is accomplished by the choke L_1 in series with the antenna lead, which, together with the shunt capacitance across the antenna primary, forms a low-pass filter. Also, the receiver chassis is insulated from the receiver case.

Some of the performance characteristics of this receiver are shown in Figs. 20 and 21. In Fig. 20, we have the receiver sensitivity as a function of signal frequency. The increased sensitivity of the receiver at the lower signal frequencies is due almost entirely to the higher gain of the r-f and mixer stages at these frequencies. The over-all sensitivity, however, is still quite good. In the second performance curve (Fig. 21), we have the variation in distortion with power output. At 2.0 watts, the distortion is 10 per cent, the latter being the recognized standard. Distortion rises fairly linearly with power output, starting from a low of 2 per cent.

Two views of this automobile receiver are shown in Fig. 22.

COMBINED TUBE-TRANSISTOR RECEIVER

An interesting application of transistors occurs in portable receivers in which vacuum tubes are employed in the converter, i-f amplifier, and second-detector a-v-c a-f amplifier while a pair of transistors, biased for class B push-pull operation, furnish the output power in place of an output tube. The advantage of this arrangement is that it frequently increases the output power yet the over-all power drain on the battery supply is reduced substantially. In a typical four-tube battery receiver, approximately 75 per cent of the relatively expensive B battery power and 40 per cent of the less expensive A battery power are consumed by the output stage (assuming a 3V4 output amplifier). When transistors are employed, the full power requirement is supplied by A batteries alone.

An illustration of what the partial conversion to transistors can mean is given by the Emerson models 747 and 838 portable receivers. The model 747, shown in Fig. 23, uses all vacuum tubes. The output tube, a 1AG4, has very limited power capabilities, and it was chosen because the model 747 receiver is exceedingly compact and only miniature batteries could be accommodated. With this line-up, the current drain on the A batteries was 160 ma. In the transistorized version of this receiver
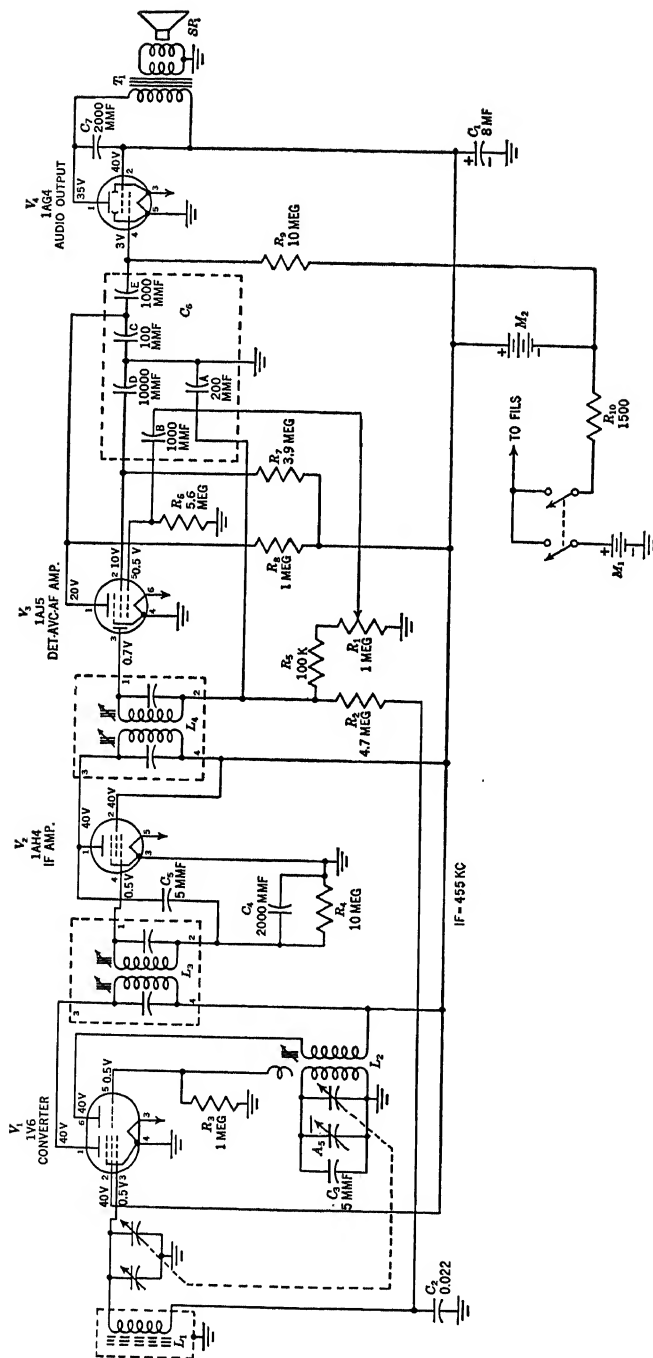
Fig. 23. The Emerson model 747 portable receiver. This circuit was subsequently converted to partial transistor operation by replacing the 1AG4 by two power transistors (see Fig. 24). (*Courtesy Howard W. Sams & Co., Inc.*)

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Fig. 24. The same Emerson receiver after the 1AG4 audio output tube had been replaced by a pair of transistors.

(Fig. 24), the 1AG4 tube was removed and a pair of matched 2N108 PNP transistors were substituted. The drain on the B battery was reduced by 25 per cent, and the total drain on the A batteries brought down to little more than 50 ma. Furthermore, with the output transistors operating in class B, the maximum power output was trebled.

The savings in power requirements would have been greater if the transistors had been used to replace a 3V4 output tube, although under these circumstances the power-output increase would not have been so startling.

The advantages gained by using this hybrid type of receiver is that tubes can be used in the more critical stages, those at the front end of the receiver, where presently available transistors still cannot equal tube performance, yet permit transistors to be employed in those stages where their lower current requirements offer definite savings in power. Of course, in this transition from vacuum tube to transistor, certain changes in design are required. For example, a miniature transformer was needed between the audio amplifier and the transistors in Fig. 24. In addition, the output transformer had to be changed.

The small 45-volt B battery in Fig. 24 is now used solely by the vacuum tubes. The A battery value has been raised to 4 volts so that it can be used by the transistors. Because of this change in A battery (from 1.5 to 4 volts), the filaments of the three vacuum tubes were connected in series. (Previously they were in parallel.)

In this chapter we have inspected a number of radio receivers which were partially or totally transistorized. No startling circuit differences were occasioned by the use of transistors in lieu of vacuum tubes; the sequence of stages still followed the same order, and similar circuitry was employed. However, the operating conditions of transistors do differ in many respects from vacuum tubes, and because of these, a number of minor circuit modifications were required.

QUESTIONS

Answer the first four questions using the transistor receiver circuit of Fig. 3.

1. a. How many transistors does the receiver employ?
   b. How does the first stage (V_1) function? Draw its equivalent vacuum-tube circuit.
2. a. What purpose does R_2 serve? R_3? C_7?
   b. Why is the emitter of V_1 tapped down on L_3?
3. a. Why is the secondary of transformer T_1 untuned?

    b. What is the purpose of C_{10} and C_{14}?

    c. Why is R_8 much larger in value than R_5?

4. How does the a-g-c system operate in the receive of Fig. 3?

5. What points of similarity exist between the a-g-c systems of vacuum-tube and transistor receivers? What are the differences?

6. Draw the diagram of a circuit utilizing the I_e form of automatic gain control.

7. Draw the diagram of a circuit utilizing the V_c form of automatic gain control.

8. Describe how the a-g-c system of Fig. 10 functions.

9. Answer the following questions about the audio stages of the receiver in Fig. 11.

    a. What is the purpose of C_{12}?

    b. How is the crossover distortion minimized in the output stage?

    c. How do the output transistors receive their biasing voltages?

Answer the following four questions about the transistor receiver circuit of Fig. 12.

10. *a.* How does the oscillator signal reach the mixer stage?

    b. Where is the incoming signal applied to the mixer?

11. Explain how the a-g-c system operates.

12. Explain how the detector stage functions.

13. What advantages does this form of detection offer? What disadvantages in comparison to diode detectors?

14. What major differences exist between the circuits of Figs. 12 and 16?

Answer the following three questions about the circuit in Fig. 17.

15. *a.* Which stages are a-g-c controlled?

    b. What form of control system (I_e or V_c) is utilized? Prove your answer.

16. What is the purpose of each of the following components: R_6, R_{18}, L_2 and C_{35}, R_5, and C_{19}?

17. What type of audio output stage is employed? What purpose do R_{29} and R_{33} serve?

18. Why is it important to inject the proper amount of oscillator voltage into the mixer? What happens if this voltage is too large or too small?

19. What advantages are gained by combining tubes and transistors in a radio receiver?

20. In which stages of a hybrid receiver are the tubes most useful, and in which stages are the transistors most useful? Justify your answer.

CHAPTER 7

TRANSISTORS IN TELEVISION RECEIVERS

The task of producing an all-transistor television receiver is considerably more difficult than the job of bringing forth a commercial all-transistor radio receiver for two reasons. First of all, many of the circuits in television receivers operate at fairly high frequencies; second, the power requirements of a number of stages, particularly those in the vertical and horizontal deflection systems, are quite high, especially so when considered from the standpoint of the power capabilities of presently available transistors.

It might be instructive to examine the frequency and power requirements of the various stages of a television receiver to see which stages could be transistorized immediately and which would require the development of other transistors.

The block diagram of a typical black-and-white television receiver is shown in Fig. 1. The various sections have been formed so that stages with similar operating requirements are grouped together. The number of stages contained in each box is not shown and, to a certain extent, is not important, because if it is possible to transistorize one stage, it would be possible to transistorize all similar stages.

THE R-F STAGES

The front end section of the receiver contains the tuner and the r-f amplifier, mixer, and local oscillator. In the v-h-f band, signal frequencies extend from 54 to 88 Mc and from 174 to 216 Mc. For u-h-f reception, a frequency coverage from 470 to 890 Mc is required. The local oscillator often generates frequencies which are 25 to 45 Mc above the incoming signals, but this, in itself, is of minor significance. If transistors can be made to operate in either the v-h-f or v-h-f–u-h-f bands, then they will certainly function up to frequencies which are 25 to 45 Mc higher.

For a transistor to be usable in these stages, it not only must be

capable of operating at these frequencies but must also do so with a fair amount of gain. Also, the noise factor of a transistor is important here because of the very low level of the incoming signal.
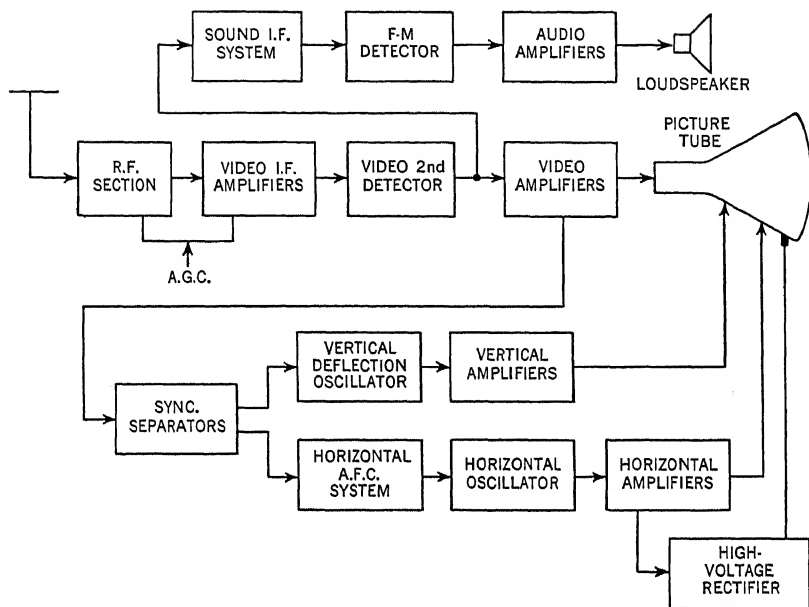
FIG. 1. A simplified block diagram of a black-and-white television receiver.

Of the three front-end stages, the requirements of the local oscillator are probably the easiest to satisfy. This is because noise is not a significant operating characteristic and because transistors will almost always oscillate at considerably higher frequencies than their cutoff value. On the other hand, for purposes of amplification, it is desirable to keep well below the transistor cutoff frequency, and this will restrict their application.

At the present time, there are no commercially available transistors suitable for use as r-f amplifiers over the television v-h-f band. The u-h-f band, of course, is even more remote, and even low-cost vacuum-tube amplifiers are not presently available for this region, let alone the newer transistors. In the mixer stage, an amplifier would be desirable, but a semiconductor diode can perform this function, and such units can be purchased in commercial quantity. As a matter of fact, present u-h-f television receivers use diodes as mixers in the front end because a suitable low-cost tube is not available.

VIDEO I-F SYSTEM

Beyond the front end are the video i-f amplifiers, and these operate at frequencies between 25 and 45 Mc. While this is still quite high, as frequencies go, it is nonetheless far enough down so that a more immediate prospect of using transistors is in view. For example, Philco engineers, in describing the applications of their surface-barrier transistors, reveal that tuned 30-Mc amplifiers of the type shown in Fig. 2 have been successfully built and operated. When using transistors at these higher frequencies, care must be taken to avoid regeneration due to the inherent feedback within the transistor. This means that some method of neutralization will be necessary. In the circuit of Fig. 2, the components R_n and C_n, together with the internal base resistance and collector capacitance of the transistor, form a bridge for isolating the input from the output.

In the circuit of Fig. 2, a surface-barrier transistor having an α cut-off frequency close to 50 Mc was employed. Over-all circuit gain was
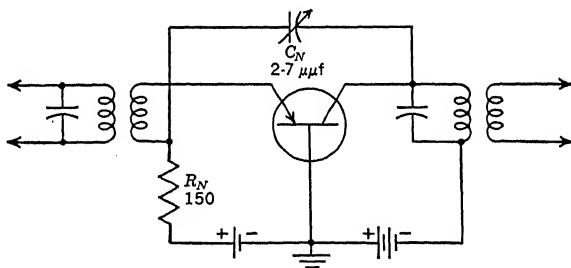
Fig. 2. The circuit of a 30-Mc amplifier using surface-barrier transistors.

13 db at 30 Mc. While this is lower than the gain achievable using miniature vacuum tubes, it does represent a workable figure. More transistors would be required than vacuum tubes for the same over-all gain. This, however, is true even at the much lower audio frequencies.

Incidentally, the same basic circuitry, involving tuned circuits and traps, would be used with transistors as with vacuum tubes. Whatever modifications did occur would arise principally to resolve the problem of matching the relatively high output impedance of a preceding stage to the low input impedance of a following stage. How this was accomplished in radio receivers was demonstrated in Chap. 6; similar approaches would be employed in television receivers.

VIDEO DETECTOR AND AMPLIFIERS

The video second detector in most vacuum-tube television receivers is currently formed by a germanium diode, so that transistorization is not required. One problem that might arise is the need for control
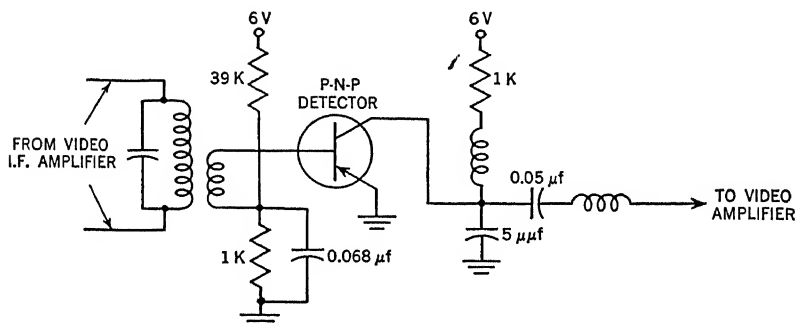
Fig. 3. A transistorized video detector.

power by the a-g-c system of a transistor video i-f system. This could best be supplied by a transistor detector of the type described in Chap. 6. In using such an arrangement, it would be necessary only to provide a wide-band coupling network so that all the video frequencies would be passed on to the video amplifiers and the picture tube (see Fig. 3). Transistors currently classified as high-frequency units would be required here because of the range of signal frequencies to be dealt with.

The video-frequency amplifiers following the second detector must be capable of amplifying a band of frequencies extending from about 30 cycles to 4 Mc. Actually, with present monochrome receivers, the gain begins to fall off at about 3.2 Mc. A suitable two-stage video am-
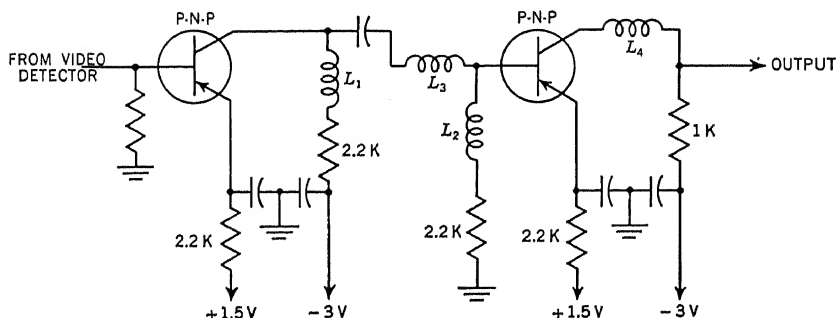
Fig. 4. A two-stage video-amplifier system.

plifier using high-frequency transistors is shown in Fig. 4. It was found in this system that if L_1, L_2, L_3, and L_4 were omitted, 28 db of gain and a bandwidth of 3.2 Mc could be obtained. When L_1 and L_2 were added, the bandwidth increased to 6.5 Mc without affecting gain, while the further addition of L_3 and L_4 produced a 9.0-Mc bandwidth. By raising the collector bias voltage, still greater voltage gains could be achieved.

One difficulty that may be experienced in designing a suitable video-amplifier system lies in obtaining sufficient voltage swing from the final stage to make full use of the contrast range of the picture tube. A peak-to-peak swing on the order of 50 volts or so is required, and this is not readily obtainable with low-power transistors.

THE SOUND SECTION

The sound system of a television receiver functions initially at 4.5 Mc and, beyond the f-m detector, at ordinary audio frequencies. Neither the i-f nor the audio stages offer any particularly difficult problems other than, in the case of the i-f system, that of obtaining transistors with a suitably high α cutoff frequency.

Either the f-m detector can be transistorized, as shown in Fig. 5, or a pair of matched germanium diodes can be employed in one of the
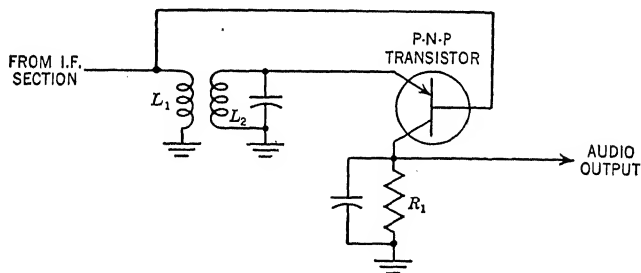
FIG. 5. A transistor f-m detector.

arrangements shown in Fig. 6. The latter two circuits are quite familiar by now, being direct germanium diode equivalents of vacuum-tube Foster-Seeley and ratio detectors. The important feature here is the use of closely matched diodes; the greater their differences, the less effective the circuit in minimizing distortion and combating amplitude modulation.

It is possible to design a transistor f-m detector using a symmetrical transistor. Briefly, this is a unit in which the emitter and collector sec-

tions are made identical so that, with the proper biasing voltage, either section could operate as the emitter or collector. (We shall refer to this type of transistor again in connection with a horizontal phase detector.)

The circuit of this f-m detector is shown in Fig. 5.* The f-m signal appearing across L_1 is applied to the base, while the voltage developed across L_2 is applied to the emitter. During the positive portion of the
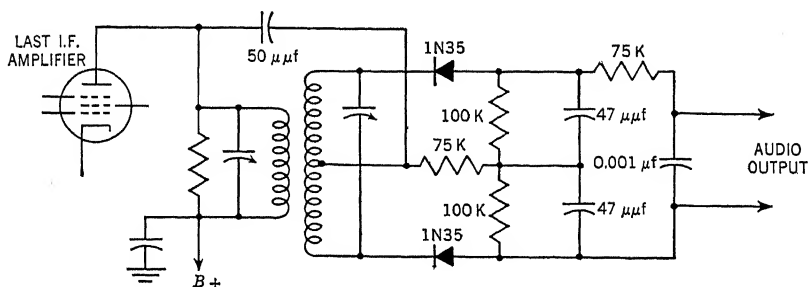
(a) Discriminator
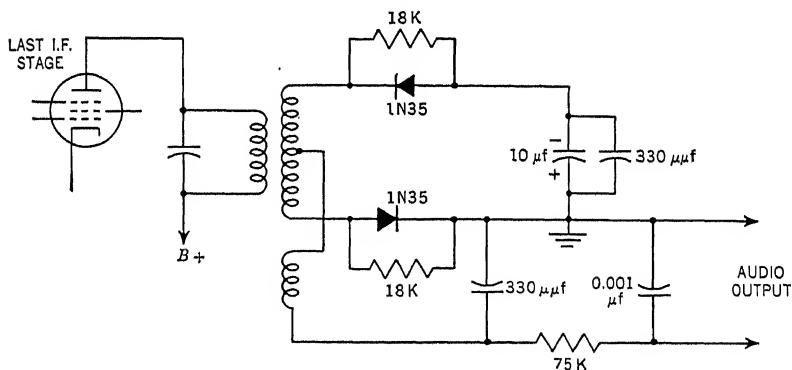
(b) Ratio detector

FIG. 6. Two types of f-m detector circuits using germanium diodes.

signal applied to the base, the emitter-collector path is open and there is no current flow through the load resistor R_1. During each negative swing, current does flow. We are discussing here a PNP transistor; for an NPN unit, the periods of conduction would be reversed.

Now the amplitude and direction of the current flow depend upon the phase relationship of the signal developed across the secondary with

* G. C. Sziklai, Symmetrical Properties of Transistors and Their Applications, *Proc. IRE,* June, 1953.

respect to the primary signal. At the resonant frequency of L_2, the voltage it develops is 90° out of phase with the voltage across the primary. During this condition, the average voltage drop across R_1 will be zero. As the applied frequency is changed, the secondary voltage lags the primary voltage by an angle less than 90° if the frequency rises, or it will lag by more than 90° if the frequency drops below the resonant (or mid) frequency of L_2. As the phase relationship changes, the voltage developed across the load resistor will vary in step with the frequency modulation.*

Changes in amplitude of the incoming signal will not affect the output as long as the signal amplitude is strong enough to operate the transistor beyond the knee of its characteristic curve (see Fig. 7). Once
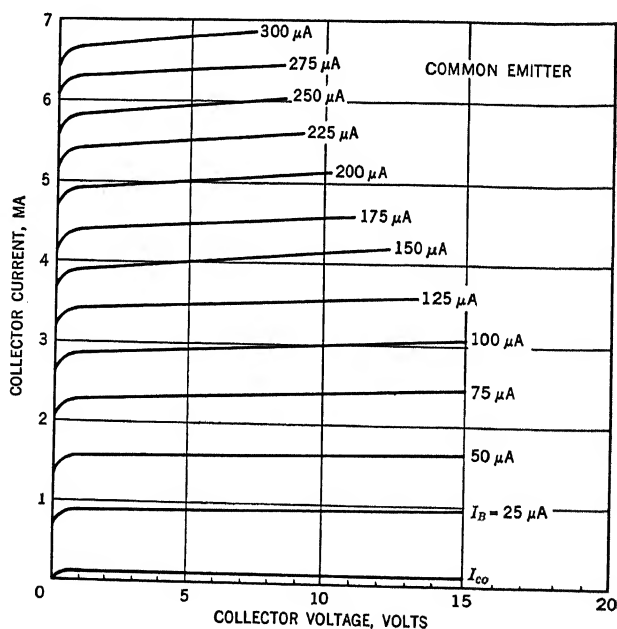
Fig. 7. Characteristic curves of a typical transistor. Note that collector current remains fairly constant with changes in collector voltage beyond the knee of each curve. This behavior is utilized in sync separators and limiters.

past this region, the collector current remains fairly constant with changes in collector voltage. Thus, because of its characteristics, the transistor will function as a limiter, too.

* A full discussion relating phase changes to f-m detection will be found in Milton S. Kiver, "F-M Simplified," 2d ed., D. Van Nostrand Company, Inc., New York, 1951.

SYNC SEPARATORS

Returning to the video system, a portion of the signal is taken from one of the video amplifiers and applied to the sync section. Here the vertical and horizontal sync pulses must be separated from the rest of the video signal. The latter voltages are then suppressed, while the sync pulses are passed on to their respective deflection systems. It is also desirable during this separation process to suppress or at least reduce the effect of any noise pulses that may be present.

In adapting transistors for sync separation, advantage can be taken of the fact (just noted) that beyond the knee of the characteristic curves, the collector current changes very little with change in collector voltage. Thus, if we drive a sync separator amplifier from cutoff to saturation, a double-clipped output voltage can be obtained possessing an amplitude that is only a few tenths of a volt less than the collector supply voltage. This is useful not only in securing a flat-topped output pulse but also in clipping any noise spikes that may be present at the sync pulse level.

A two-stage sync separator is shown in Fig. 8.* The first transistor is of the PNP variety, while the second is an NPN unit. Both transistors
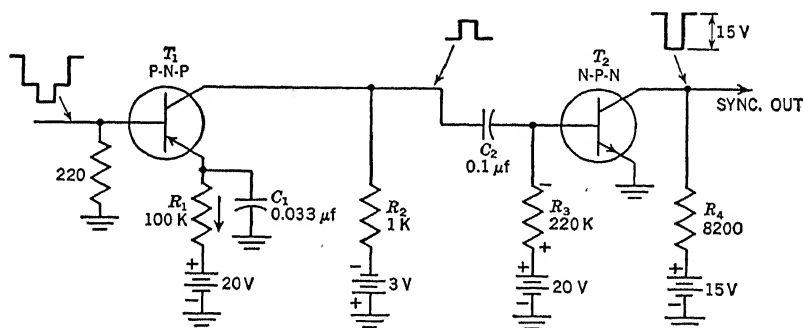
FIG. 8. A two-stage sync separator. (*Courtesy RCA Review.*)

should preferably have α cutoff frequencies in excess of 3 Mc so that the steep sides of the vertical and horizontal sync pulses will be reproduced. (A low-frequency transistor would tend to slow the rate of voltage rise and change the steep sides to sloping sides.) The video input signal to the sync separator should be in the sync pulse negative phase and should come from a low-impedance source. It is desirable to

* H. C. Goodrich, Transistorized Sync Separator Circuits for Television Circuits, *RCA Rev.*, December, 1955.

have the first sync separator stage conduct only while the sync pulses are active and to cut off or become nonconductive in the interval between sync pulses. This is achieved in T_1 of Fig. 8 through the combination of R_1 and C_1. When the sync pulse arrives, it causes the transistor to conduct, with emitter current flowing through R_1 in direction indicated by the arrow. This surge of current develops sufficient bias across the R_1C_1 combination so that at the end of the pulse interval, the base-emitter junction is reverse biased and all current flow through the transistor is halted until the arrival of the next sync pulse.

Note that this is a self-biasing arrangement in which the emitter current will vary with signal amplitude, producing corresponding voltage variations across R_1 and C_1. In this respect it is similar to the cathode-biased vacuum-tube separator frequently used. Self-biasing is desirable here because it enables the operating condition of the stage to change in step with the level of the incoming signal. The reader will appreciate that such variations exist even in receivers employing automatic gain control.

The amplified sync signal appears at the collector of T_1 and is passed on to T_2. This second stage is operated so that it is driven into saturation during sync by any usable signal. This provides sync pulses of uniform amplitude and cuts off any noise pulses at sync level.

Strong overdriving of a sync amplifier must be avoided because it leads to an output pulse which is wider than the input pulse.[*] This broadening will cause a phase shift in many types of horizontal phase detectors and is therefore undesirable. To prevent this overdriving, self-bias is employed on transistor T_2. This is achieved through the combination of C_2 and R_3. When the incoming signal tends to drive T_2 far beyond saturation, the base-emitter circuit develops a voltage across R_3 (with the polarity indicated) which reduces the extent of the overdriving.

The sync pulse developed at the collector of T_2 has a peak-to-peak amplitude of 15 volts and is negatively phased. If the opposite polarity is desired, a phase inverter, such as that described in Fig. 32, Chap. 4, may be employed.

Advantage can be taken of the sync clipping capabilities of a transistor driven from cutoff to saturation to develop a useful one-stage sync separator (see Fig. 9). R_1 and C_1 again form a self-biasing arrange-

[*] The explanation for this effect is that while collector saturation limits the collector current to a value equal to its bias voltage divided by the load resistance, overdriving produces a flow of charges from the emitter into the base in excess of this limit. Some of these excess carriers are stored in the base and continue to flow to the collector after the input signal has fallen to zero.

ment to prevent pulse broadening while at the same time providing clipping action at all levels of input signal, from the very weak to the very strong. It will be appreciated, however, that because a single stage is being employed, the preceding amplifier must be capable of supplying a greater video input current for proper separation.
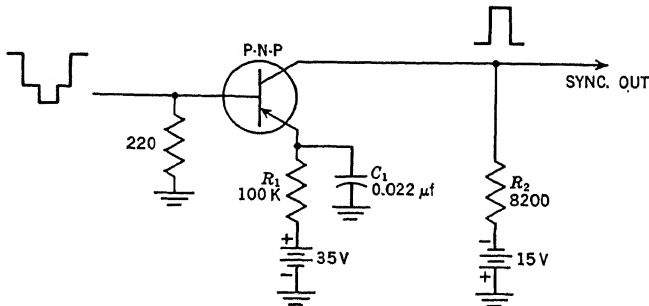
FIG. 9. A one-stage sync separator. (*Courtesy RCA Review.*)

A more elaborate version of the foregoing sync separator is shown in Fig. 10. This circuit not only produces flat-topped sync pulses but also provides a measure of immunity against blocking caused by strong noise pulses. It accomplishes the latter goal by means of a dual time-
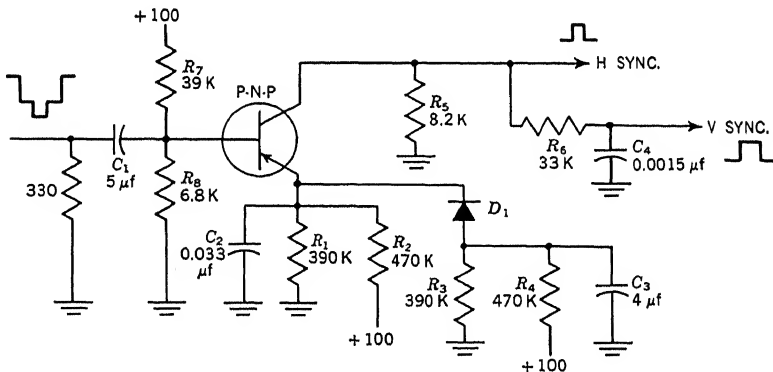
FIG. 10. A one-stage sync separator with a dual-time-constant network. (*Courtesy RCA Review.*)

constant network in the emitter circuit, coupled with a special germanium diode D_1. The manner in which this dual network functions is as follows:

Upon the arrival of a sync pulse, the emitter current of the transistor will bias D_1 in the forward direction, causing it, in effect, to become a

closed switch. This will bring the long-time-constant network of R_3, R_4, and C_3 into the circuit and permit the effective separation of the vertical sync pulses. (A long separation time constant is needed to accomplish this separation.) Now, if a strong noise pulse should come along, capacitor C_3 will charge to its peak value. When the noise passes, the weaker normal sync pulses will be unable to provide D_1 with enough countervoltage to cause it to conduct, forcing D_1 to remain open and removing C_3 with its excess charge from the circuit. Horizontal syncpulse separation will now be achieved using the bias developed across the short-time-constant circuit of R_1, R_2, and C_2. When the excess charge on C_3 has drained off,* the long-time-constant network will reestablish itself actively in the circuit. By means of this arrangement, the horizontal noise immunity of the sync separation is improved by an average factor of 8 to 1 over systems not employing a double-time-constant circuit.

VERTICAL DEFLECTION SYSTEM

Beyond the sync separator stages, the sync pulses branch off into the vertical and horizontal deflection systems. Of the two sections, the vertical system is the simpler, first, because it does not require an automatic-frequency-controlling network and, second, because its power requirements are considerably lower. Not only must the horizontal system swing the scanning beam back and forth across the screen 15,750 times a second, compared with only 60 times a second in the vertical section, but it should also be able to develop a suitably high accelerating voltage for the picture tube. (The latter action need not necessarily be performed by the horizontal section; however, it is desirable to utilize the energy released during the retrace interval if this can be achieved.)

One output from the sync separator section is passed through an integrating filter and then applied to the vertical sweep oscillator. This may be either a blocking oscillator or a multivibrator, and typical circuits for each type were shown in Chap. 5. Beyond this would come several vertical amplifiers and then a vertical output stage. A typical

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* This occurs long before the next vertical sync pulse arrives. It is permissible to use a long-time-constant network to assist in the separation of the horizontal and vertical sync pulses *as long as* there are no strong noise pulses present. If noise pulses are present, they could easily block or inactivate the sync separator for many horizontal sync pulses, permitting the horizontal sweep oscillator to slip out of synchronization. In the above arrangement, this is avoided by the use of D_1 and the alternate short-time-constant circuit.
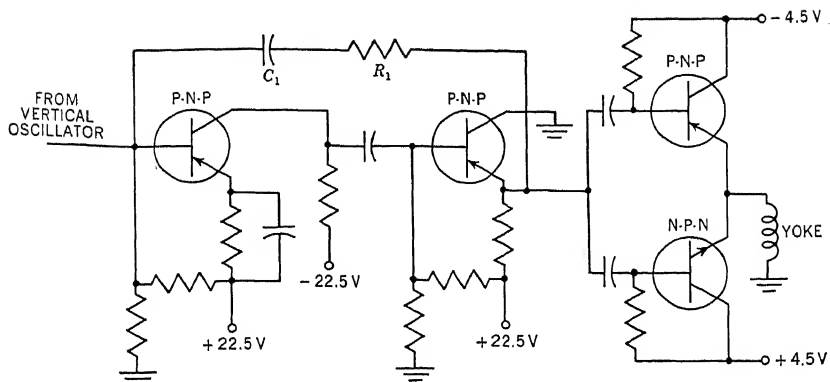
FIG. 11. An amplifier system suitable for a vertical deflection system.

arrangement is shown in Fig. 11. The first two stages are grounded-emitter amplifiers with some frequency-selective feedback through R_1 and C_1 to compensate for distortion introduced by these stages. The output stage consists of a grounded-collector push-pull amplifier using an NPN and a PNP transistor in a complementary symmetrical arrangement. Through this means, the vertical windings of the yoke can be directly coupled to the two emitters without the presence of a decentering current. An operating efficiency for this class A amplifier of 24 per cent is claimed, which compares very favorably with the maximum theoretical efficiency of 33 per cent obtainable (for a saw-tooth wave).* The deflection current through the yoke is shown in Fig. 12.

FIG. 12. The voltage waveform across the yoke in Fig. 11.

HORIZONTAL DEFLECTION SYSTEM

A second sync pulse output from the sync separator stages is directed to the horizontal deflection system. Let us now turn our attention to this section of the receiver.

The susceptibility of the horizontal sweep oscillator to noise pulses and other forms of interference has led to the universal use of automatic-frequency-control networks ahead of the horizontal oscillator. Whatever the form of the control system, its method of achieving con-

* G. C. Sziklai, R. D. Lohman, and G. B. Herzog, A Study of Transistor Circuits for Television, *Proc. IRE*, June, 1953.

trol is by comparing the frequency of the generated sweep voltage with the frequency of the arriving horizontal sync pulses. If a frequency difference exists, a corrective voltage is developed which, when fed back to the horizontal oscillator either directly or indirectly, causes the generated frequency to change until it is equal to that of the incoming pulses.

A widely employed vacuum-tube a-f-c network is shown in Fig. 13. Its transistor counterpart appears in Fig. 14. To appreciate the opera-
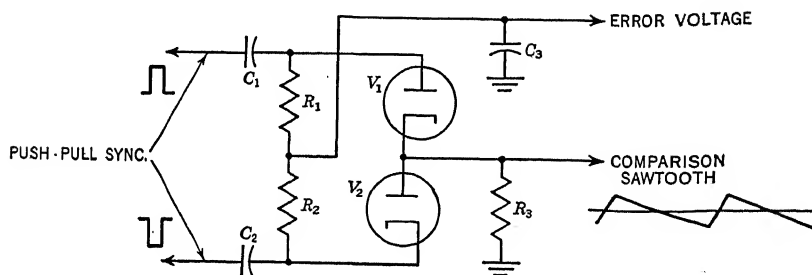
Fig. 13. A conventional double-diode phase detector. (*Courtesy RCA Review.*)

tion of the latter circuit, let us examine first the circuit of Fig. 13 and see how it functions.

The two diodes are seen to be connected in series with each other. This produces a cathode (of V_1) and plate (of V_2) which are directly connected together. From this point, a resistor connects to ground.
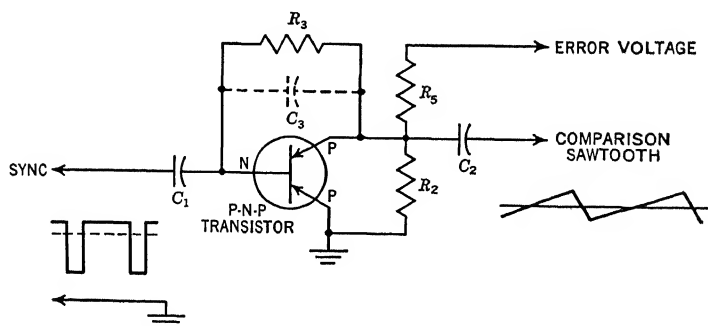
Fig. 14. Basic transistor phase-detector circuit. (*Courtesy RCA Review.*)

Coming into this network are two horizontal sync pulses of opposite polarity (representing the received signal) and a saw-tooth wave (representing the generated deflection voltage). The latter signal is ob-

tained from a point beyond the horizontal sweep oscillator so that it will reflect the frequency being generated by that stage.

As a first step, let us disregard the saw-tooth voltage and observe the effect of the two sync pulses. The positive sync pulse is applied to the plate of V_1, and if we were concerned only with this sync pulse and the circuit of V_1, then the simplified circuit would appear as shown in Fig. 15. Application of the positive pulse causes current to flow from the plate of V_1 to the right-hand plate of C_1 and from the left-hand plate of C_1 through the signal source (i.e., a prior stage) to ground and then up through R_3 to the cathode of V_1. The time constant of this circuit is low enough so that C_1 charges to the peak value of the applied pulse. During the interval between pulses, C_1 discharges through R_1 and C_3, developing voltage drops across these two components with the polarity as indicated in Fig. 15. When the next pulse arrives, C_1 is
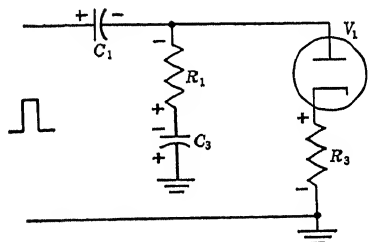
FIG. 15. The circuit of V_1 in Fig. 13.   FIG. 16. The circuit of V_2 in Fig. 13.
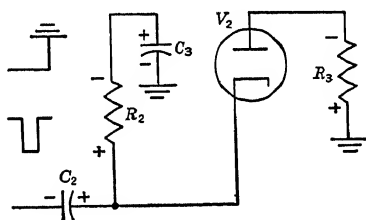
recharged to the full peak value. The current flow through V_1 is thus in spurts which are generally shorter than the applied pulses themselves.

At the same time that this is happening, negative sync pulses are being applied to the cathode of V_2 and causing current to flow through this tube. A simplified arrangement of this portion of the network is shown in Fig. 16. The current travels from the plate of V_2 down through R_3 to ground and from here to the signal source and C_2 and then to the cathode of V_2. The polarity of the voltage drop across R_2 and C_2 caused by this current is indicated in Fig. 16. Note that the voltage drop across R_3 produced by the current from V_2 is opposite in polarity to the voltage drop developed across this same resistor by V_1. If, as is usual, both incoming sync pulses possess the same amplitude and both tubes conduct equally well, then the net resultant voltage across R_3 is zero.

During the interval between pulses, capacitor C_2 discharges through R_2 and C_3, developing voltage drops across these two components with

the polarity indicated in Fig. 16. Again the net resultant voltage across C_3, owing to the two discharge currents that flow through it, is zero. And since it is the voltage present across C_3 that represents the corrective or error voltage to the horizontal oscillator, then with the sync pulses acting by themselves, no net voltage is produced. This is as it should be.

By the same line of reasoning, if we ignore the sync pulses and concern ourselves solely with the saw-tooth wave applied to R_3, then we see that since V_1 and V_2 will be driven alternately into conduction for equal periods of time and with equal-amplitude voltages, the net output voltage across C_3 will again be zero.

With both types of voltages applied to this circuit sumultaneously, comparison of the two signals will take place only at the instant that the sync pulses arrive, for it is only at this moment that V_1 and V_2 conduct and are therefore in a position to respond to the saw-tooth voltage applied across R_3. Three situations are possible.

First, if the sync pulses arrive at a time when the saw-tooth wave is passing through zero, then we have a situation which is similar to that discussed above when the saw-tooth voltage was ignored. The net voltage developed across C_3 is zero. This indicates that the frequencies of the sweep oscillator and the sync pulses are in step with each other.

The second situation occurs when the sync pulses arrive and the saw-tooth voltage is positive at this instant. Under this condition, V_2 will conduct more strongly than it will if the saw-tooth wave is zero, and C_3 will charge to a higher peak value (because now two series-aiding voltages are driving current through V_2). At the same time, the positive saw-tooth voltage is also being applied to the cathode of V_1, and for this tube it is working against the applied sync pulse. Hence, the total current through V_1 will decrease and produce a smaller voltage drop across C_3. The net voltage across C_3 will be governed by the current from V_2 and will be positive with respect to ground. The horizontal sweep oscillator will thus receive a corrective voltage which, if the circuit is designed properly, will serve to alter its frequency so that the saw-tooth voltage at R_3 will be passing through zero when the sync pulses arrive.

The third situation occurs when the saw-tooth voltage is negative when the pulses arrive. Now V_1 conducts more strongly than V_2, and a net negative voltage will develop across C_3. This opposite-polarity voltage will have an opposite effect on the frequency of the horizontal sweep oscillator.

In a transistor phase-detector circuit, similar operation can be achieved by means of a single transistor in a circuit such as that shown in Fig. 14. The transistor, however, is specially constructed so that the

collector and emitter junctions are equal in area. (In the transistor designed for general usage, the collector occupies a greater area than the emitter.) This forms a symmetrical transistor. Advantage is taken of the fact that transistors will conduct in either direction to form this phase detector. That is, the biasing voltages to emitter and collector can be reversed so that the element which serves as an emitter under one set of conditions becomes a collector under another set of voltages. In short, either element can serve as the emitter or collector, depending upon the applied potentials. It is common, therefore, to refer to either element as a "collector-emitter." This behavior, too, is the reason both emitter and collector in Fig. 14 are shown with arrowheads.

Operation of this transistor phase-detector circuit depends on the transistor conducting only when the sync pulses are present. Thus, if the instantaneous saw-tooth voltage across R_2 is positive at the instant the negative sync pulse triggers the base on, then the uppermost element with the arrowhead is serving as the emitter and the lower
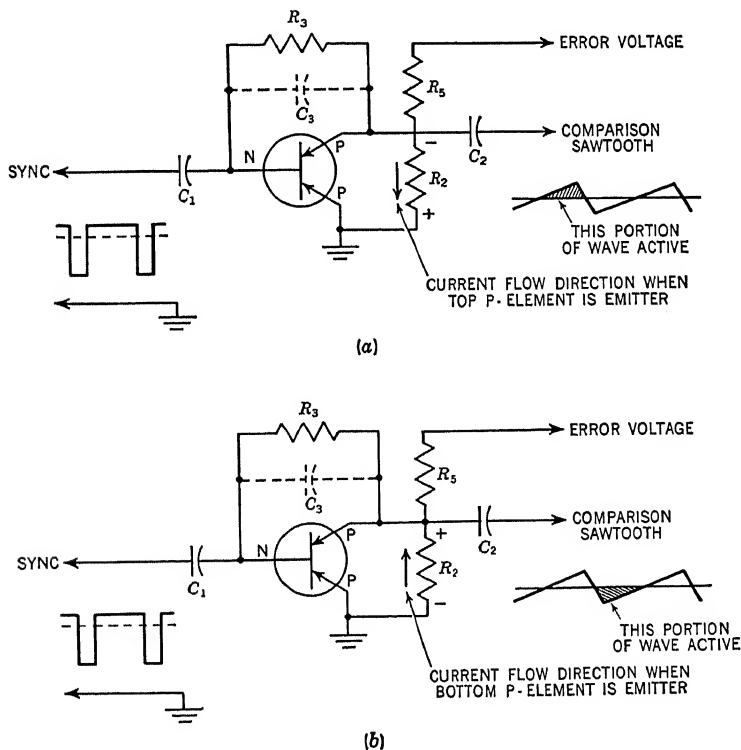
FIG. 17. The changing direction of current flow through R_2 when the polarity of saw-tooth voltage reverses during sync interval.

arrowed element is the collector. This is because this is a PNP transistor and, for conduction to occur, the emitter must be positive with respect to the base. Electrons then travel in the direction indicated in Fig. 17a, producing a negative voltage drop across R_2. The potential represents the error voltage which is transferred, via R_5, to the horizontal control tube.

Conversely, if the saw-tooth voltage is negative when the sync pulses arrive, then the element previously acting as the emitter now becomes the collector and the other P section becomes the emitter. Current flow is reversed now through R_2 (see Fig. 17b), and a positive error voltage is produced. In this way the transistor acts as a bidirectional switch producing an error (or correction) voltage whose polarity depends on the part of the saw-tooth cycle active at the instant the sync pulses arrive.

If the saw-tooth wave is passing through zero when the pulses arrive, no voltage appears across R_2.

In order for the circuit to function properly, the transistor must be completely cut off between sync pulses. This is achieved by having the peak-to-peak sync voltage at the base exceed the peak-to-peak saw-tooth voltage. When the sync pulses are active, the current that flows in the base circuit causes C_1 to charge to their peak value. In the interval between pulses, this charge decreases very slowly, keeping the
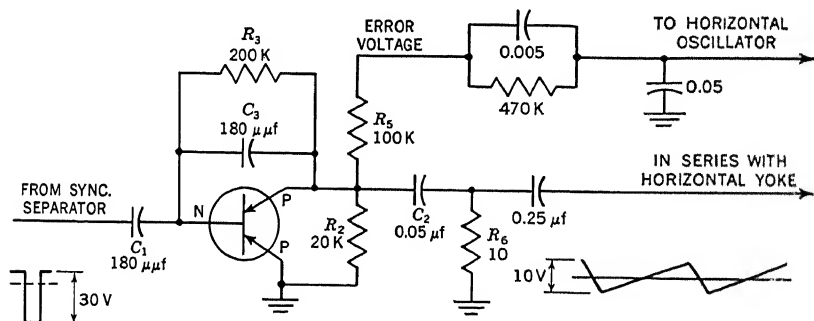
FIG. 18. A phase-detector circuit with suitable component values. (*Courtesy RCA Review.*)

base at all times positive enough with respect to the collector-emitter voltage to prevent conduction.

A representative phase-detector circuit with component values is shown in Fig. 18.* The incoming sync pulses are supplied by a sync

* B. Harris and A. Macovski, A Symmetrical-transistor Phase Detector for Horizontal Synchronization, *RCA Rev.*, March, 1954.

separator section, while the comparison saw-tooth wave is obtained from the horizontal output transformer or horizontal yoke windings. As in vacuum-tube circuits, if a saw-tooth wave is not directly available, a pulse is taken from the output circuit and transformed into a saw-tooth wave by integration.

The purpose of R_3 in Figs. 17 and 18 is to help increase the collector current that flows during the sync-pulse interval. It does this by increasing the base current on which the collector current is dependent. C_3 is added to maintain the balance of the circuit both when the top arrowed element acts as the emitter and when the bottom arrowed element serves in this capacity. The values of C_1 and C_3 are limited by the capacitance which their series combination shunts across the sync separator. Too large a value integrates the leading edge of the sync pulse and results in excessive picture shift with respect to the raster.

The value of R_6 is chosen to provide the proper peak-to-peak amplitude of saw-tooth wave. This must be kept much smaller than the peak-to-peak value of the sync pulses.

Another version of the same phase-detector circuit is shown in Fig. 19. Basic operation remains the same, but the appropriate circuit must
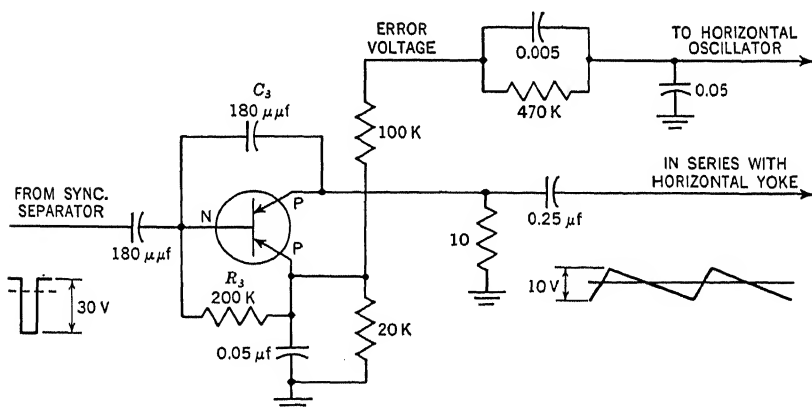
FIG. 19. Another version of the phase detector shown in Fig. 18. (*Courtesy RCA Review.*)

be used in conjunction with the proper saw-tooth polarity in order to obtain the correct sense of oscillator control. Both circuits require negative sync pulses.

The rest of the horizontal system, with the exception of the oscillator, is, at the present time, very much in doubt. (The oscillator, of course, is in the audio range, and any one of several circuits described in Chap.

5 could be employed for this purpose.) A considerable amount of power is required to swing the scanning beam back and forth 15,750 times a second, and commercial transistors currently available possess neither the power capabilities to perform this task nor the voltage insulation to withstand the high peak pulses which appear in the horizontal output circuit. The most immediate solution in sight is to employ transistors up to the horizontal output stage and then utilize a vacuum tube for this final amplifier.

Wherever possible, in the foregoing discussion, actual workable circuits have been shown. However, much work remains to be done before television receivers are either partially or totally transistorized. Undoubtedly, partial use of transistors in television receivers will occur first. The day of the fully transistorized receiver, even for a relatively small screen, is still several years off.

QUESTIONS

1. Why would it be more difficult to transistorize completely a television receiver than a radio receiver? Give several specific examples.

2. Draw the circuit of a transistor detector suitable for use in a video system.

3. What advantage would a transistor video detector possess over a diode detector? Draw a diagram of a diode video detector.

4. Draw the diagram of a two-stage video-amplifier system. Explain the purpose of each component.

5. Indicate what precautions would have to be observed in designing a transistorized video i-f system for a television receiver. (Note: Cover such items as α cutoff frequency, temperature stability, impedance matching, etc.)

6. What characteristics of a transistor enable it to be used successfully as a limiter? As a sync separator?

7. Explain how the circuit of Fig. 8 functions.

8. Why is a double-time-constant arrangement, such as used in Fig 10, more desirable than a single-time-constant network?

9. What is the indicated reason for the pulse-broadening effect when a sync separator stage is strongly overdriven?

10. Describe the operation of the sync separator of Fig. 10.

11. What is a symmetrical transistor? What counterpart does it have among vacuum tubes?

12. Draw the circuit of a vacuum-tube phase detector. Explain its mode of operation.

13. Draw the basic circuit of a transistor phase detector. Explain briefly how it operates.

14. Why must the incoming sync pulses in the circuit of Fig. 14 possess much larger amplitudes than the saw-tooth wave applied to the same circuit?

15. Draw the complete circuit of an actual transistor phase detector. Explain the purpose of each component.

CHAPTER 8

ADDITIONAL TRANSISTOR DEVELOPMENTS

Vacuum tubes, at the outset of their development, contained only a filament and a plate. This was the diode. Eventually, Lee De Forest added a third element, the grid, and the triode came into being. As time went on and engineers became electronically more sophisticated, other elements were added, until today there is a vast assortment of tube types and structures capable of performing an almost incalculable variety of jobs.

In analogous fashion, the initial work on semiconductor electronic devices started with the diode, then followed with the triode and more recently the tetrode. In addition, variations, modifications, and new structural types of semiconductor devices are being constantly developed, and there is every reason to believe that after a number of years, there will be as many different transistors as there are tubes, each designed to perform best within a certain range of applications.

It is the purpose of this chapter to examine the operation of those "other" transistors which have been developed to date. Some of these will bear a very close resemblance to the transistors already discussed; others will be entirely different.

PHOTOSENSITIVE TRANSISTORS

An application for which the transistor is receiving almost as much attention as for amplification is its use in photoelectric equipment such as flame detection, automatic door openers, light dimmers, burglar alarms, counters, and the like. The interest in this particular direction is spurred on by the fact that whereas phototubes deliver microamperes of current, phototransistors deliver milliamperes. This means that intermediate amplifiers which are needed with phototubes to build up the minute currents to usable proportions can, with photosensitive transistors, often be eliminated. In addition, there is a further saving in power

because of the lack of filament heating and a greater efficiency in power utilization where amplification is achieved.

A phototransistor that was developed by the Bell Telephone Laboratories is shown in Fig. 1.* The heart of the device is a pill-shaped wafer of germanium having a spherical "dimple" ground in one side so that
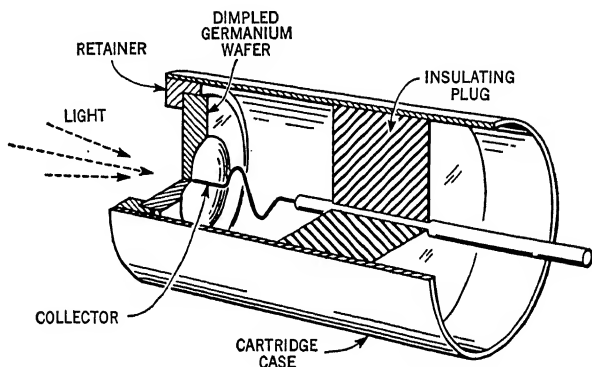
Fɪɢ. 1. A phototransistor that was developed by Bell Telephone Laboratories.

the thickness of the wafer at the center is about 0.003 in. The wafer is forced-fitted into one end of a metal cartridge, and a pointed phosphor-bronze wire is brought into contact with the wafer at its center. This wire is called the collector. The far end of the wire fastens to a metal pin embedded in an insulating plug which is held in position at the opposite end of the cartridge. (The second electrical contact to this phototransistor is the cartridge case itself.)

The wafer is made of N-type germanium; hence it contains an excess of electrons. The area directly beneath the collector wire becomes, under the action of a forming current, P-type germanium. This gives us a diode which will function in the same manner as other PN junction diodes previously described. That is, if it is biased in the forward direction, current will flow easily; if it is biased in the reverse direction, only a minute current will flow. In its present application, this phototransistor is biased in the reverse direction and the small current that flows is called the "dark" current. When light is directed on the germanium wafer, the amount of current flowing increases in proportion to the light intensity. This is explained rather simply by the fact that the energy which the germanium wafer absorbs from the light quanta serves to break a number of covalent bonds, producing equal

* J. N. Shive, The Phototransistor, *Bell Lab. Record,* vol. 28, no. 8, pp. 337–342, August, 1950.

numbers of electrons and holes. Under the influence of the applied electric field, the electrons travel to the positive terminal of the battery (which connects to the case) and the holes go to the negative battery terminal (which is tied to the collector). Current flow through the circuit is thus increased.

A characteristic of this phototransistor is that maximum current response is obtained when the incident light rays fall in the immediate neighborhood of the point where the collector wire contacts the wafer. Figure 2 illustrates how the photocurrent varies as a tiny spot of light
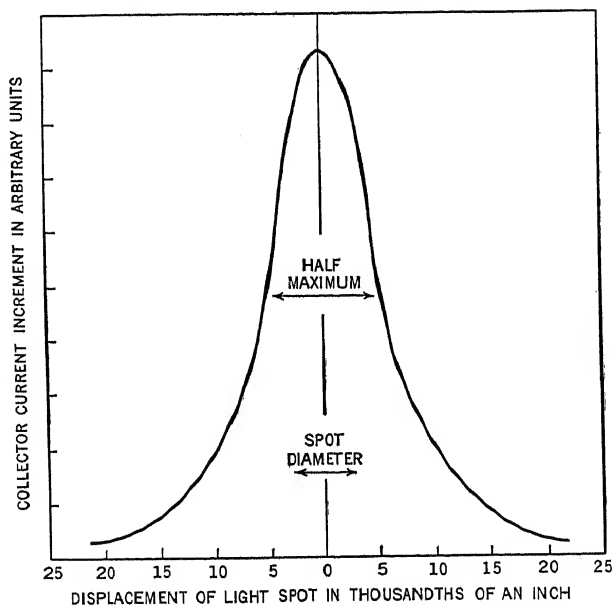
FIG. 2. Manner in which the current output will vary as a spot of light is moved across the responsive area of the phototransistor shown in Fig. 1.

is moved across the center of the responsive area of a typical phototransistor. It is apparent that permitting light to fall uniformly over the germanium surface is wasteful of the light energy. To prevent this, these phototransistors are combined with small glass lenses that focus the arriving light rays into a narrow beam which is restricted principally to the desired area. The reason for this behavior is that those electrons and holes which the light quanta produce at points relatively far from the PN junction point recombine before they reach the junction. The greatest possibility of avoiding recombination occurs at the junction point; the longer the distance that the electrons and holes must

travel, the greater the possibility of recombination with an opposite charge.

A set of characteristic curves showing the collector current for various light intensities is given in Fig. 3. While the load shown is a resistance, it could just as well be a relay, an amplifier, or whatever other device the phototransistor is designed to activate.
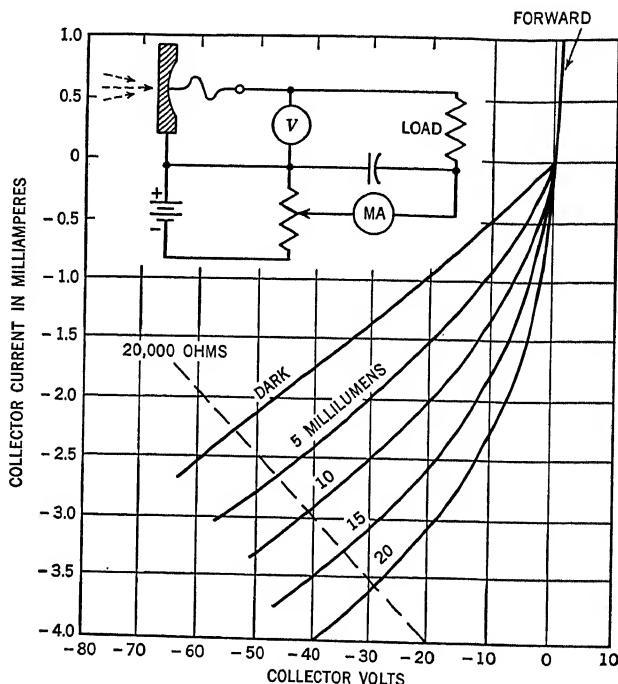
Fig. 3. Characteristic curves of the phototransistor showing the collector current for various light intensities. The load line for a 20,000-ohm load resistor is also indicated. (*Courtesy Bell Telephone Laboratories.*)

It was noted in Chap. 1 that light quanta must possess a certain minimum amount of energy in order to move an electron from a lower to a higher level. Since the energy of a light quanta varies inversely with the wavelength of light, it follows that the photoconductivity response will depend upon the wavelength of the incident light. Figure 4 shows this dependence for the phototransistor of Fig. 1. The long wavelength limit occurs in the vicinity of 2.0 microns. Thereafter, as the wavelength becomes smaller, the response rises sharply and then slowly starts to fall off.

An interesting sidelight is the observed behavior that when the

quantum energy of the incident light becomes sufficiently great, electrons may be given enough of a "push" to enable them to escape completely from the germanium wafer. The substance now becomes photoemissive. To achieve this effect with germanium would require that
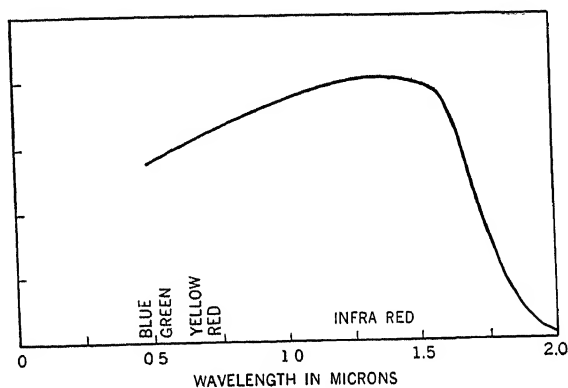
FIG. 4. The relative quantum efficiency (in arbitrary units) versus the wavelength of the incident light for the phototransistor of Fig. 1.

ultraviolet light be employed. Since only the photoelectric effect is desired ordinarily, conventional incandescent light sources are employed.

The phototransistor just described is of point-contact construction. A similar unit possessing a PN junction assembly may also be devised with comparable results (see Fig. 5). Here, too, response will be great-
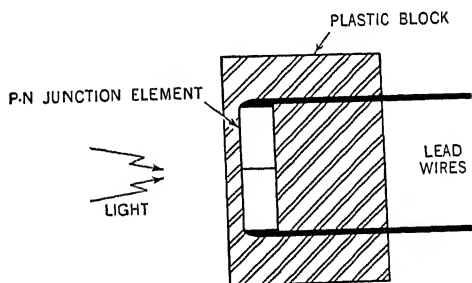
FIG. 5. A junction phototransistor.

est when the light is directed at the junction; it will drop off gradually as the distance from the junction increases.

Another form of phototransistor employs an NPN type of construction in which only the central base section is photosensitive (see

Fig. 6). No connection is made to the base. However, a voltage is applied across the two end sections. The end to which the negative battery is connected is the emitter; the other end section serves as the collector. Without any external voltage at the base forcing the holes
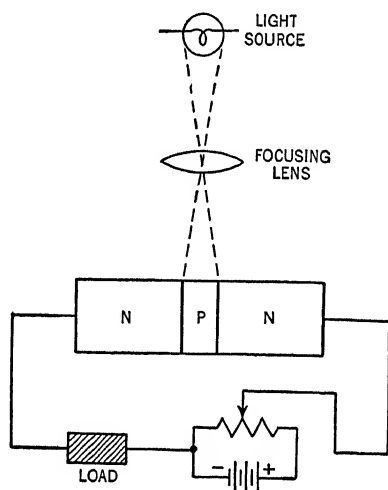
FIG. 6. An NPN phototransistor. Light is directed onto the photosensitive center section.

here to move toward the emitter junction, combinations at this junction with emitter electrons are quite low and only a minute current flows through this transistor. However, when light is focused on the photosensitive P section, holes are formed in sufficient quantity to produce as much as 4 to 6 ma of current through the load. With this amount of current, a relay can be operated directly.

The current-amplifying properties of a transistor are also utilized in this application. That is, a small change in emitter-base potential, produced here by light, results in a sizable change in collector current.

The P zone must be made exceedingly thin. Furthermore, each of the two N sections, especially the emitter, must have low resistivity. To raise the current flow for a specific light intensity, the applied voltage can be made greater within the permissible dissipation limits of the transistor.

Two applications of the foregoing phototransistor are shown in Fig. 7, and the simplicity of each circuit is immediately apparent. The first diagram (Fig. 7a) is that of a photoelectric counter. Light is collected and focused on the sensitive base region of the phototransistor by a

collecting lens. The unit develops several milliamperes of current which flow through and actuate a sensitive relay. Closing the relay discharges a capacitor through a mechanical counter.

Such a device will work on an ordinary pocket flashlight at distances up to 50 ft and in broad daylight.
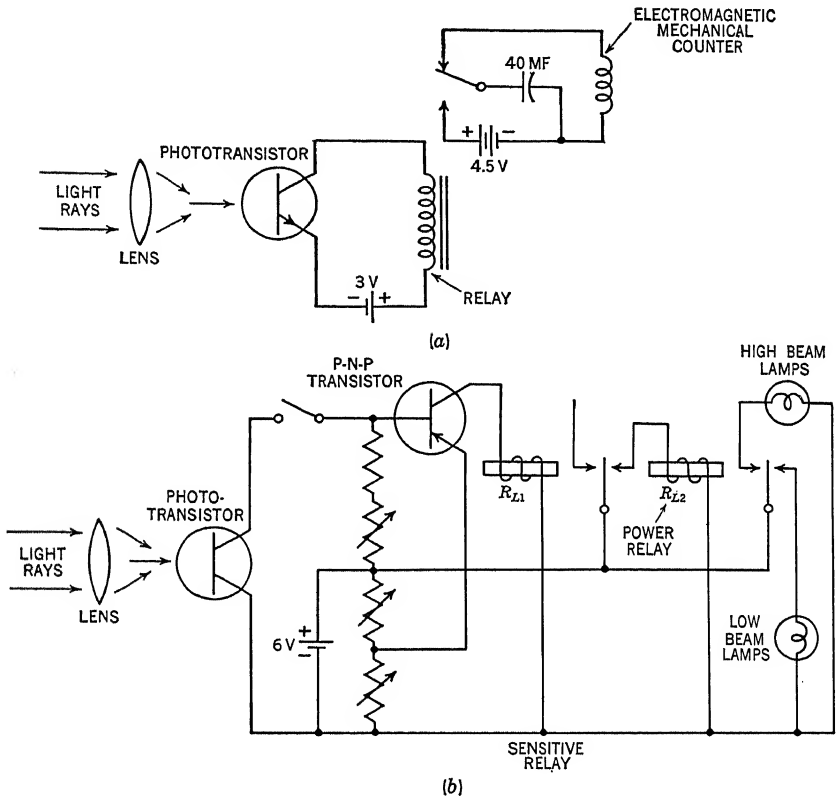
Fig. 7. (a) Circuit diagram of a phototransistorized counter. (b) The phototransistor employed to dim automobile headlights automatically.

Figure 7b presents the diagram for an automatic automobile-headlight dimmer. The circuit contains the phototransistor with a single grounded-emitter amplifier in a d-c network. A voltage divider provides two sources of voltage from a single power supply. These voltages are placed essentially in opposition (by adjusting the variable resistors) so that the base current to the transistor is near zero. This reduces the effect of dark current in both the phototransistor and the transistor.

When no light is reaching the phototransistor, no collector current is

flowing through the PNP transistor and relay R_{L1} is not actuated. Under this condition, the relay arm touches the right contact, closing the path for R_{L2} and actuating this relay. This pulls the contact arm of R_{L2} to the left, and the high-beam lamp is turned on. When an oncoming car appears, collector current does flow, the arm on R_{L1} is drawn to the left, and the current path through R_{L2} is opened. This releases the R_{L2} arm, and it swings to the right, completing the circuit for the low-beam lamp.

Still another phototransistor design is shown in Fig. 8. The unit is basically an NPN transistor except that both N sections have been specially treated for photosensitivity. When light is directed at the left-hand PN junction, an internal voltage is generated which causes a current to flow through the phototransistor and the external load without the need for a power supply. When the same light is focused on the right-hand PN junction, a similar voltage is developed which causes current to flow through the phototransistor and the load in the opposite direction.

One application of this device is shown in Fig. 9.* Beams from lamps L_1 and L_2 are focused onto the phototransistor. L_1 may be a standard
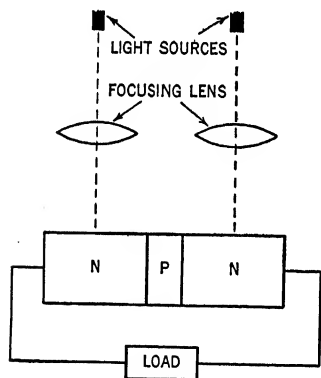
FIG. 8. An NPN phototransistor in which both N sections are made photosensitive.
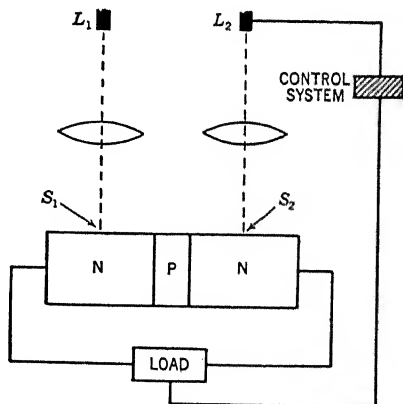
FIG. 9. An application of the NPN transistor of Fig. 8 to light control.

lamp with fixed intensity, while the intensity of L_2 may be variable. The lamps illuminate S_1 and S_2, two points which are equidistant from the two junctions. When the lamps are equally bright, they generate

* Patent 2,641,712, Raymond J. Kircher, Summit, N.J. (Assigned to Bell Telephone Laboratories, Inc.)

equal and opposite voltages and no current flows through the load. If L_2 grows brighter, the net voltage across the transistor load will be negative; less light from L_2 will produce a voltage which is positive.

These fluctuations in output voltage are fed to a control device. When the voltage is negative, L_2 is made dimmer; when the voltage is positive, L_2 is made brighter. Thus the circuit tends to maintain the lamps equally brilliant.

The circuit arrangement in Fig. 9 may be employed in photographic exposure-control processes, in stage light-intensity-control systems, and in infrared baking processes. It may also be employed in translating or transcribing systems for coding, decoding, and information blending systems.

FOUR-TERMINAL TRANSISTORS

A major goal in transistor development has been to extend the range of frequencies over which these devices will operate. Several methods of dealing with this problem have been discussed previously, and several additional methods will be covered here. One of these is the four-terminal transistor, or transistor tetrode. This transistor is basically an NPN junction unit of the type already described. However, a fourth electrode, labeled b_2, is attached to the base layer at a point which is on the side opposite the original base connection b_1 (see Figs. 10 and 11). A potential is applied to this second base lead which is consider-
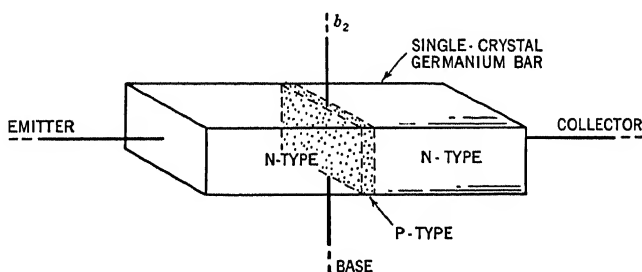
FIG. 10. A transistor tetrode.

ably higher than the normal emitter-to-base potential. The latter voltage is generally on the order of 0.1 volt. On the other hand, b_2 is given a potential of about -6 volts. This voltage is fixed and will not vary with the signal, since the latter still is applied between the emitter and base b_1.

The presence of this large bias voltage at b_2 will modify the flow of current through the transistor. In the unit shown in Fig. 10, the emitter and collector sections are formed of N-type germanium and the base of P-type germanium. The application, then, of a relatively large negative potential to b_2 serves, in the base region under the influence of this voltage, to restrict the flow of electrons from the emitter to the collector sections.
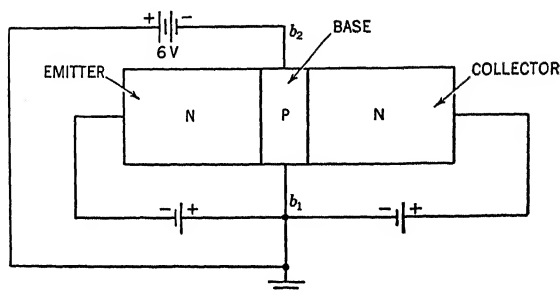
FIG. 11. The transistor tetrode with suitable d-c biasing voltages. While not shown, the incoming signal would be applied to the emitter and the load resistor would be inserted in the collector circuit.

It can be seen from Fig. 11 that the −6 volts is applied between b_2 and b_1, or, actually, across the length of the base region. Since the base has an internal resistance, the voltage decreases uniformly from −6 volts at the top to 0 volt at the bottom. The voltage is negative enough to all points except near the bottom edge of the base to prevent any flow of electrons from the emitter across the base to the collector. At the bottom edge, the 0.1-volt forward bias between b_1 and the emitter will permit electrons to travel from emitter to collector.

Thus, the addition of connection b_2 and the application of a negative voltage here alter the flow lines in the conventional NPN transistor to the extent shown in Fig. 12. The ability of this modification to improve the high-frequency operation of this transistor stems from two factors. First, the collector capacitance is reduced by decreasing the effective active area of the collector junction. This capacitance acts to shunt the signal around the output of the transistor and is analogous to the output capacitance of a vacuum tube. The smaller the capacitance, the higher the signal frequency at which its shunting effect becomes important. Second, the effective area of the base is reduced substantially, which means that the active base resistance is reduced. A low base resistance, we have previously seen, is conducive to improved high-frequency operation.

A limitation of this tetrode construction is the fact that by forcing the currents to flow in a narrow channel, we reduce the current rating and thereby the power capabilities of the unit. Fortunately, the power requirements of many of the high-frequency stages in commercial receivers are quite low, so that this restriction is not of prime importance in many applications.
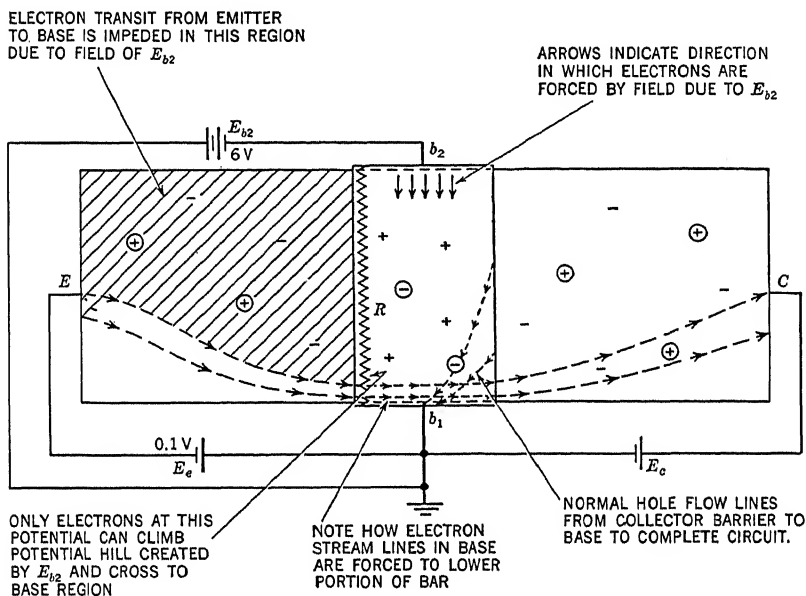
FIG. 12. The flow of carriers in the transistor tetrode. Note how little of the base section is actually used.

The ability of the tetrode transistor to extend the range of an amplifier is demonstrated by the graphs shown in Figs. 13 and 14. In the first diagram, the top curve shows the variation in α with frequency when the second base connection is open. The transistor now is functioning as a conventional NPN unit. When b_2 is connected and a current flows (here 1.5 ma) through this element, the α value is lower but its decrease with frequency is more gradual. The curves cross over at about 30 Mc; thereafter the operation of the tetrode is definitely superior to that of an NPN triode.

The frequency improvement produced by this new transistor is perhaps more clearly brought out in Fig. 14. Here we have the measured and computed gains for the tetrode amplifier shown in Fig. 15. When
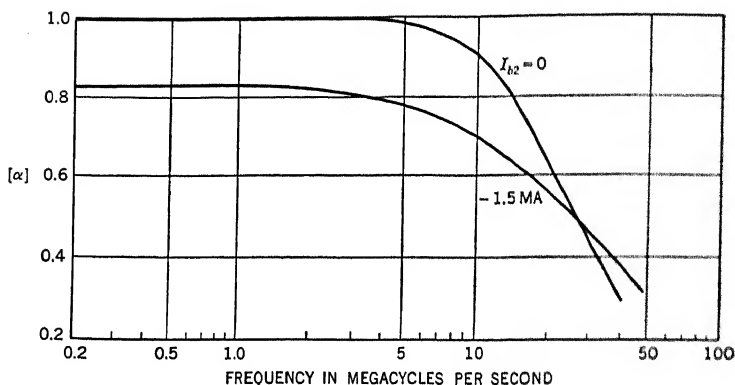
FIG. 13. The variation of α with frequency for a transistor tetrode connected as a conventional NPN unit (top curve) and as a true tetrode (lower curve). (*Courtesy IRE.*)

b_2 is left unconnected, the drop in gain starts at about 300 kc and becomes quite appreciable above 1 Mc. Compare this behavior with that obtained when b_2 is used. Results are given for two values of load resistors. Now the gain, although attaining a lower maximum value than before (when b_2 was not connected), remains flat up to 3 Mc (when $R_L = 5,100$ ohms) and 7 Mc (when $R_L = 2,460$ ohms). The usable range greatly exceeds these frequencies; in the graphs shown, 12 db of gain can be obtained at 20 Mc. This represents a sizable step upward in frequency and would enable such tetrode transistors to be useful in the i-f stages of television receivers.
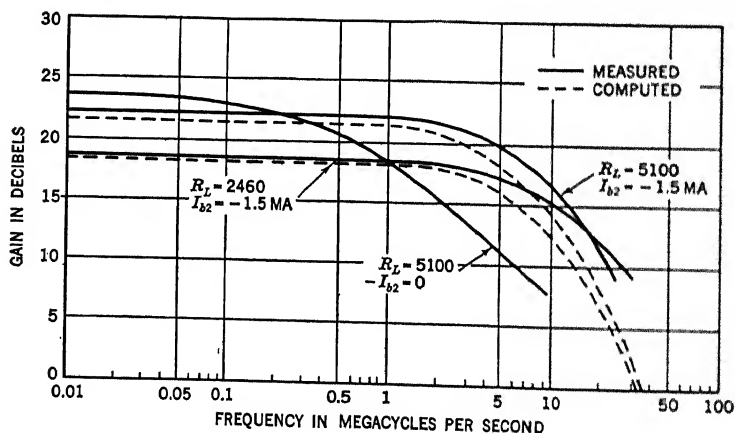
FIG. 14. Measured and computed gains for the amplifier shown in Fig. 15. (*Courtesy IRE.*)
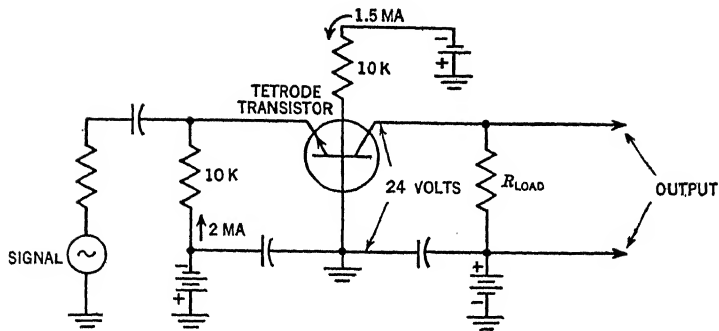
FIG. 15. The tetrode amplifier used in obtaining the response curves shown in Fig. 14. (*Courtesy IRE.*)

Active use of b_2, rather than the passive role indicated above, has also been suggested. For example, in Fig. 16a, the tetrode transistor is employed as a modulator. The r-f carrier signal is applied to the emitter, while the audio voltage is impressed at b_2. Both the emitter base b_1 and the base b_2 biasing voltages are obtained from the same bias bat-
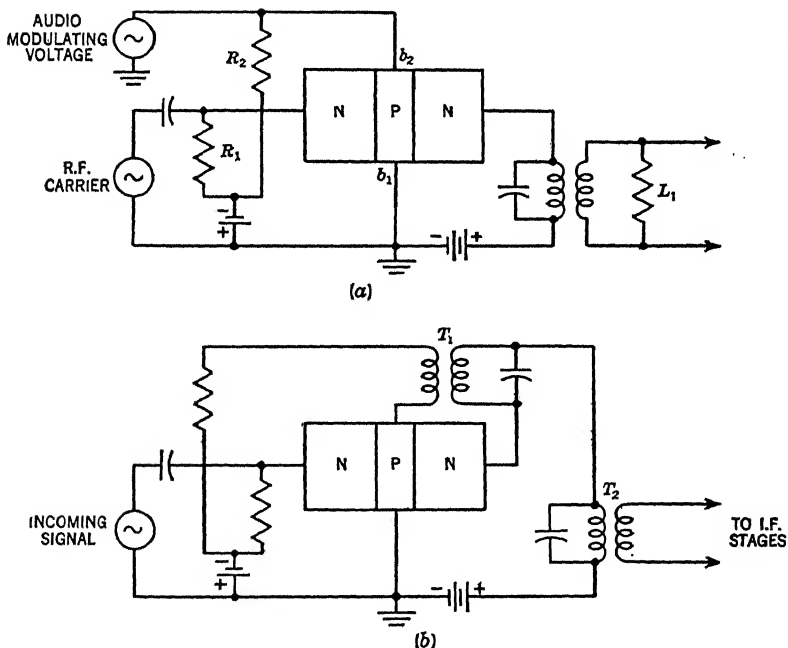
FIG. 16. (*a*) Tetrode transistor employed as a modulator. (*b*) Tetrode transistor connected as a frequency converter.

tery, although each circuit is isolated from the other by resistors R_1 and R_2. The changing audio voltage affects the amount of carrier current flowing through the transistor and, in this way, alters or modulates its amplitude. The modulated signal appears across load L_1 for transference to the rest of this system.

In Fig. 16b, the tetrode transistor is shown connected as a frequency converter. Transformer T_1 feeds energy back from the output, or collector, circuit to the b_2 base terminal. If the polarity of the feedback voltage is correct, oscillations will occur. At the same time, the received signal is applied to the emitter. Interaction of this signal with that from the local oscillator produces sum and difference frequencies. Transformer T_2 is tuned to the i-f or difference-frequency signal, and this is then fed to several i-f amplifier stages, as in any conventional radio receiver.

The tetrode transistor is seen to possess many application possibilities, and a number of firms are beginning to manufacture such transistors in quantity. Two such units are shown in Fig. 17. Just how

(a)   (b)
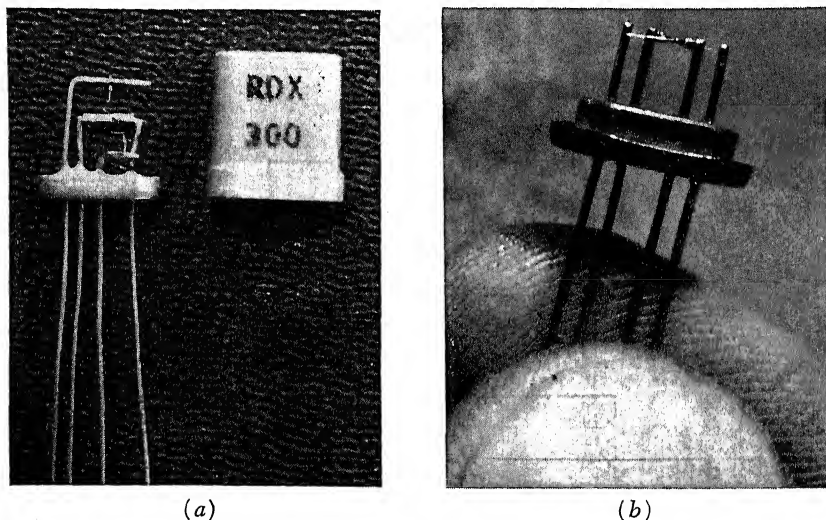
FIG. 17. Views of two tetrode transistors. (a) Manufactured by Germanium Products Corporation. (b) Product of Bell Telephone Laboratories.

much actual use will be made of this transistor will depend upon its cost and its ability to compete with some of the other transistor developments discussed here and elsewhere in this book.

THE PNIN AND NPIN TRANSISTORS

Another transistor which holds considerable promise of raising the high-frequency limits of present triode transistors is the PNIP (and its complementary NPIN) transistor developed by the Bell Telephone Laboratories. An illustration of this type of transistor is shown in Fig. 18. It consists of an emitter, a base, and a collector, which are similar to
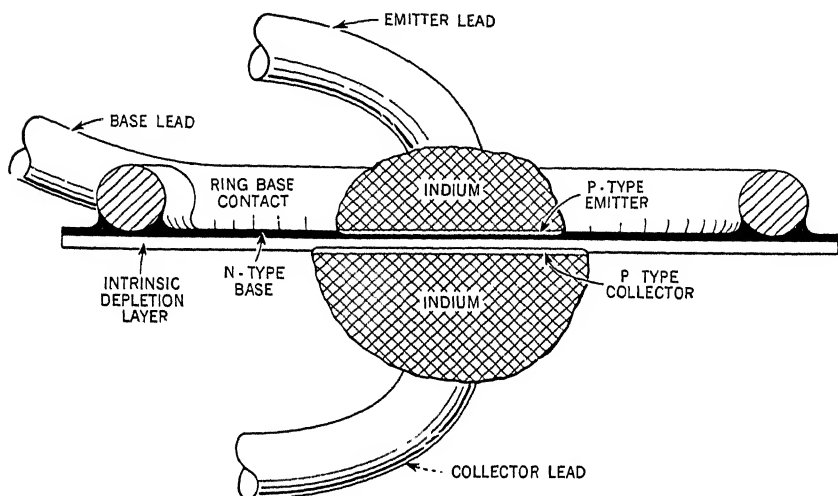
FIG. 18. Sectional view of a PNIP transistor. (*Courtesy Bell System Technical Journal.*)

previously described junction transistors, plus an additional layer of pure germanium which is inserted between the base and collector sections. This slab of pure germanium is almost completely free of excess electrons and holes. For this reason it is also called intrinsic germanium, and it is from this latter designation that the "I" in the heading PNIP is obtained.

To appreciate the purpose that the additional germanium layer serves, it might first be desirable to examine, in perhaps greater detail than heretofore, some of the factors which limit the frequency response of a junction transistor.

There is, first of all, the thickness of the base section. The carriers which the emitter injects into the base section must travel across this thin layer and arrive at the collector junction. In a PNP transistor, the carriers from the emitter are holes; in an NPN transistor, electrons

perform this function. In either case, the carriers travel across the base by a process of diffusion, and this requires a small but finite (or measurable) time. Now if all the injected carriers required exactly the same travel time, the net effect would be simply to delay the output signal with respect to the input signal. However, in this travel, not all the carriers take the same path, and consequently, the carriers (holes or electrons) corresponding to a particular part of the input signal do not all arrive at the same time at the collector. When the signal frequency is relatively low, this minute time difference of arrival can be ignored. As we increase the signal frequency, however, some of the late-arriving carriers begin to interfere with the carriers representing the next portion of the signal, with resultant disturbance and cancellation effects. At this point the amplitude of the output signal begins to fall off. The dispersive effect becomes more and more pronounced as the signal frequency rises, and the frequency response continues to decrease.

To minimize this effect, the base section should be made very narrow. However, as we make the base thinner, we steadily decrease the reverse voltage which can be applied between it and the collector section. Also, with exceedingly thin base layers, irregularities in thickness or in impurity distribution may result in a collector-to-emitter short-circuit effect called "electrical punch-through."

Another factor that wields considerable influence on the extent of the transistor frequency response is the resistance of the base section. As indicated in a prior discussion (Chap. 3) of transistor equivalent circuits, this base resistor r_b is common to both input and output circuits. Consequently, it introduces a certain amount of degeneration just as an unbypassed cathode resistor does in a vacuum-tube amplifier. This feedback, or degeneration, reduces the output impedance of the device. It also leads to an increase in the over-all output capacitance of the transistor, and both effects serve to reduce the voltage and power gain of the unit. It would thus be desirable to reduce the resistance of the base section, and one way to do this would be by increasing its thickness. This, however, runs directly counter to the conclusion reached above, i.e., that the base should be made thinner to reduce carrier diffusion time.

One partial solution to this impasse was noted in the alloy junction transistors described in Chap. 3. Here, the base layer directly between the emitter and collector sections was made exceedingly thin, but immediately beyond this area, the base widened out (see Fig. 19). The high-resistance area of the base is kept small, and this helps to maintain the over-all base resistance low (or at least lower than it was before).

It is also possible to reduce the base resistance by adding a higher percentage of impurities (donors or acceptors) during the formative process. This, however, is not too desirable because the more conductive the base becomes, the lower the collector-to-base breakdown voltage and the lower the β rating of the transistor. Furthermore, a low base resistance serves to increase the base-to-collector capacitance.
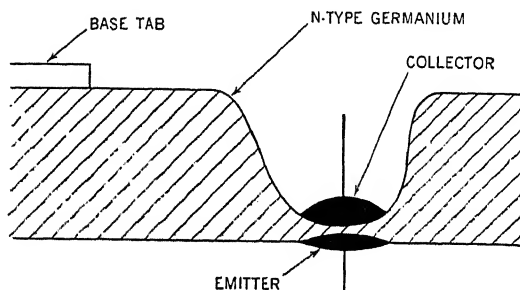
FIG. 19. Basic construction of an alloy junction transistor.

The various internal capacitances of a transistor also serve to influence its frequency response. If we consider a PNP transistor, for example, then a cross-sectional view might appear as shown in Fig. 20. Of particular interest at the moment is the PN junction between emitter and base and the same junction between base and collector. When there are no bias voltages applied to the transistor, the width of both PN junctions are identical. With no applied bias, there is a tendency for holes in the emitter section to cross over into the base section and a similar tendency for electrons in the base section to diffuse into the emitter section. However, as soon as a relatively small number of electrons and holes do cross their respective section boundaries, an unbalance of charge is created in both regions. That is, the emitter section tends to become more negative (owing to loss of holes and the gain of some electrons) and the base region tends to become more positive (owing to the loss of some of its electrons and the acquisition of emitter holes). All further tendency of this action to continue is thus rather quickly discouraged by the electrostatic potential which is built up across the junction.* Since there is a charge existing across the junction, and in consequence a small potential difference, we have in essence a small capacitance. The capacitance of this region is that of a parallel-plate capacitor having a plate separation equal to the thickness of the junction layer. In similar fashion, a capacitance exists between the base and the collector regions at their junction.

* This, of course, is the potential hill previously mentioned in Chap. 2.

The width, or spread, of the two junctions will change when bias voltages are applied. For example, since the base-emitter junction is biased in the forward direction, the width of this junction becomes quite narrow. On the other hand, the base-collector junction is reverse biased, and the extent of this junction increases as the collector voltage
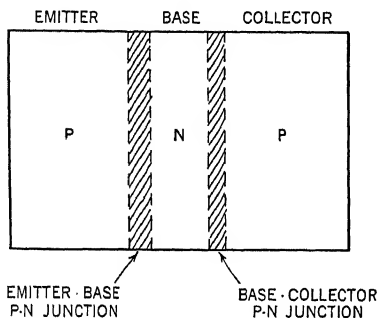
FIG. 20. A PNP transistor and its two PN junctions. No bias voltages applied.
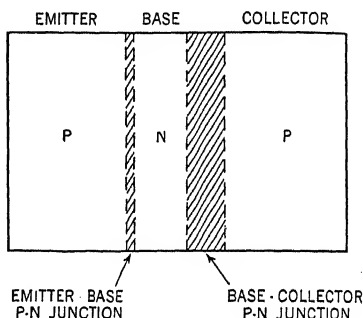
FIG. 21. When bias operating voltages are applied to a transistor, the emitter-base PN junction narrows while the base-collector PN junction widens.

increases (see Fig. 21). The latter occurs because the applied voltage appears principally across this junction and it serves to strengthen the existing electrostatic field by widening the junction width so as to bring more fixed donor and acceptor charges into the field. During the course of operation, the bias voltages at both junctions will vary with the signal, and these capacitances will vary also.
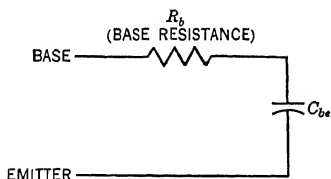
FIG. 22. The combination of base resistance R_b and base-emitter capacitance C_{be} forms a low-pass filter in the transistor input circuit.

To keep the effect of the emitter capacitance small, a low base resistance is required because the base resistance is essentially in series with this capacitance. (Emitter resistance is part of this input circuit too, but emitter resistance is usually much lower than base resistance.) As a matter of fact, the combination of base resistance and emitter-base capacitance forms a low-pass filter of the type shown in Fig. 22. To raise the frequency of the highest signal which this filter will pass, R and C should both be as small as possible. In the case of the collector capacitance, a low value is also desirable because this capacitance shunts the output circuit. This capacitance

can be reduced by making the area of the collector junction smaller, but this reduces the transistor current rating and, with it, the maximum power rating. Collector capacitance can also be reduced by employing higher collector voltages, since the greater the reverse voltage, the wider the spread of the base-collector junction. The limit on the collector voltage, however, is governed by the width of the base layer and its internal resistivity.

In the PNIP transistor a number of changes have been made in order to take as much advantage of the high-frequency capabilities of a transistor as possible. For example, the base and collector regions are separated by the relatively wide intrinsic germanium layer. This means that in essence, we have widened the base-collector junction and thereby lowered its capacitance. This aids the frequency response. (Remember that the slab of intrinsic germanium possesses no excess electrons or holes and therefore it cannot provide the charges necessary to form a PN junction with either the base on one side or the collector on the other.)

With the collector positioned at a greater distance from the base, we can now make the base quite thin without fear of a voltage breakdown between it and the collector. Also, base substances of much lower resistivities may be employed, thus producing lower ohmic base resistances. Finally, to reduce the effect of the emitter-base junction capacitance, the emitter area is made smaller.

Bias voltages are applied to the PNIP transistor in the same fashion that they are in conventional junction units. That is, the emitter is biased in the forward direction and the collector is biased in the reverse direction. These voltages are with respect to the base; the intrinsic layer is not given any external potential.

When operating biases are applied to this device, holes are injected by emitter into the N base region and then diffuse across this region until the intrinsic region is reached.* At this point they travel through the I region at high velocities to the collector. Carrier travel through the I region is much faster because there are no donor or acceptor charges to reduce the strength of the applied voltage (produced by the base-collector battery).

Units produced in the laboratory have produced stable gains without compensation of 20.5 db at 10 Mc, and oscillators have been built up

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* The carriers, in this instance holes, travel most slowly through the base region because it is practically field free. That is, whatever voltage is applied between base and emitted appears almost wholly across the junction separating these two regions. By the same token, whatever voltage is applied between base and collector appears across the junction separating these two regions.

to 95 Mc. It is indicated that amplifiers may be built to operate at 1,000 Mc with 10 db or more gain.

PNPN TRANSISTORS

An interesting development in junction transistors which gives promise of values of α in excess of 1 is the PNPN transistor. The arrangement of the various sections of this device follows the sequence shown in Fig. 23. Each P zone has an excess of holes; each N zone an excess of
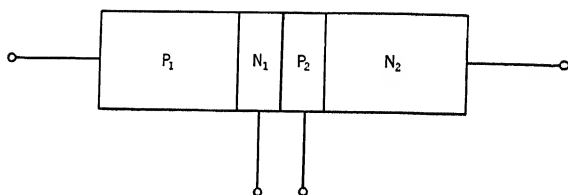
Fig. 23. A PNPN transistor.

electrons. The two inner sections have a width on the order of 0.002 in., while the two outer sections are about 0.050 in. thick.

A typical circuit in which this unit may be employed is shown in Fig 24. P_1 is the emitter, N_1 is the base, and P_2 is the collector. The load, or output, circuit, however, is not connected to P_2. Instead, it is connected to N_2, the section which follows P_2. However, P_2 and N_2 are interconnected by R_2, and the behavior of this device is governed in large measure by the value of this resistor. More on this in a moment.
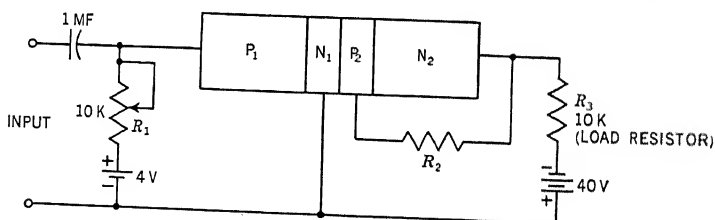
Fig. 24. A typical circuit for the PNPN transistor.

The junction between P_1 and N_1, which we shall call J_1, is biased in the forward direction. Junction J_2, between N_1 and P_2, is biased in the reverse direction. This stems from the negative voltage which is applied to P_2 by resistor R_2. Hence, if we consider only P_1, N_1, and P_2, then we have a conventional PNP transistor in which each section receives the proper bias voltages. On the other hand, if we start from the

opposite end, then we have another transistor, consisting of N_2, P_2, and N_1. This is of the NPN variety, and if we check the polarity of its bias voltages, we find that N_2 is the emitter, P_2 is the base, and N_1 is the collector.

In this somewhat novel combination of a PNP transistor with an NPN transistor, the object is to employ the current variations in one unit, here the P_1, N_1, and P_2 transistor, to produce even greater current fluctuations in the second transistor, here formed by N_2, P_2, and N_1. If the current variations in the first section are initiated by an incoming signal, then the final result will be a greatly enlarged replica of this signal across the load resistor. Here is how this desired action comes about.

When the incoming signal is applied to P_1, corresponding current variations are set up through P_1, N_1, and P_2. The principal current carriers in P_1 are holes, and these travel through N_1 and through P_2. At the right-hand edge of P_2, junction J_3, these holes encounter the positive field of the N_2 region donors, and the holes tend to pile up at this junction. In essence, what they do is establish a positive space charge which fluctuates in accordance with the voltage variations of the incoming signal.

At the same time electrons from the N_2 region are attempting to travel from N_2 through P_2 to N_1 and thence back to the battery (40 volts) and the load resistor to N_2 again. The presence of the positive-
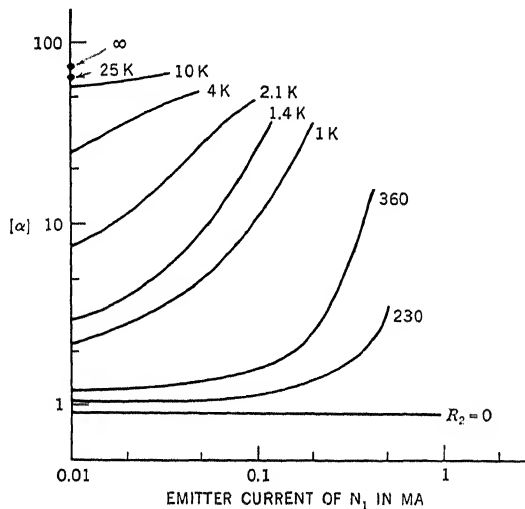
FIG. 25. The values of α which can be obtained from the NPNP transistor as R_2 is varied in value.

hole space charge at junction J_3 aids this electron flow, permitting an increased number of electrons to flow. Furthermore, the instantaneous amplitude of this electron current is regulated by the instantaneous fluctuations of the positive space charge at junction J_3. Hence, the electron current is modulated at the signal frequency, producing an amplified version of the incoming signal across the load resistor.

The values of α which can be realized with this device are shown in Fig. 25. When R_2 is zero, the P_2 and N_2 sections are shorted together and we have a conventional PNP transistor with an α value slightly less than 1. As R_2 increases in value, the obtainable values of α range up to 50 and more. A practical limit is reached when R_2 is on the order of 10,000 ohms. Beyond this value, α remains nearly constant as the emitter current is varied.

Sections N_1 and P_2 should be as narrow as possible, otherwise the device will not function satisfactorily. The N_1 region is the base for the P_1, N_1, P_2 combination, and it is desirable to have it as narrow as possible in order to get as many of the P_1 holes over to the P_2 region. By the same token, P_2 serves as the base area for the electrons traveling from N_2 to N_1, and this, too, should be quite narrow.
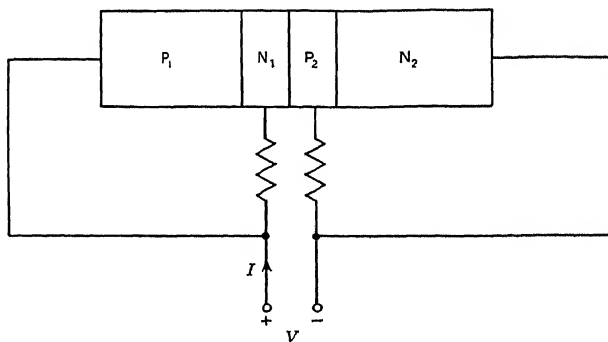
FIG. 26. The PNPN transistor connected to function as an electronic switch or trigger circuit.

To summarize, then, we see that the incoming signal regulates the flow of holes through P_1, N_1, and P_2 and that these holes form a positive fluctuating space charge at junction J_3 which then controls a large electron current flowing from N_2 to N_1.

The PNPN transistor can also be employed to serve as an electronic switch or trigger circuit. For this use, the unit is connected as shown in Fig. 26. The reason the transistor can function in this manner is

indicated by the current-voltage characteristic of this circuit (see Fig. 27). As the voltage is increased from zero to value V_P (about 50 volts), the current I increases slowly to a maximum and the resistance of the circuit is positive and large. However, at the maximum voltage V_P, the device drops into the negative resistance state, indicated by the curve between V_P and V_S. That is, the current increases with decreasing voltage. This is the sort of negative resistance condition which is useful in electronic switches. At V_P, we have a high-voltage and high-
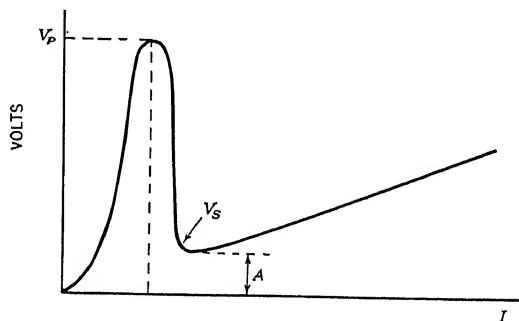
FIG. 27. The manner in which the circuit of Fig. 26 operates.

resistance condition with low current. This is essentially an open-switch condition. Beyond V_P, we have low voltage and high current, which represents a closed-switch condition.

Once the closed-switch condition is established, the only way to open the circuit is to bring the voltage back to zero or at least to a value which is lower than the voltage represented by A. The latter might be called the critical value of the circuit.

TWO-EMITTER TRANSISTOR

Somewhat analogous to the preceding four-terminal junction transistor is a recently announced four-terminal point-contact transistor (see Fig. 28). The additional contact to the normal three-electrode transistor serves to increase the α factor to values in excess of 20.

The fourth terminal is biased (with respect to the base) to function as an emitter. Furthermore, in order to obtain the sizable increase in α, this second emitter must be placed relatively far from the collector. If the second emitter is spaced close to the collector, no increase in the normal α of the device is observed. Under these conditions, the two emitters tend to operate independently of each other. However, when

the second emitter is positioned at a distance relatively far from the collector, then it acts in consort with the first emitter, greatly increasing the α of the transistor. This is explained as follows.*

Since the transistor is of the PNP variety, each of the emitters will inject holes into the transistor interior. The holes produced by the normal emitter Number 1 are indicated symbolically by $\oplus$; those
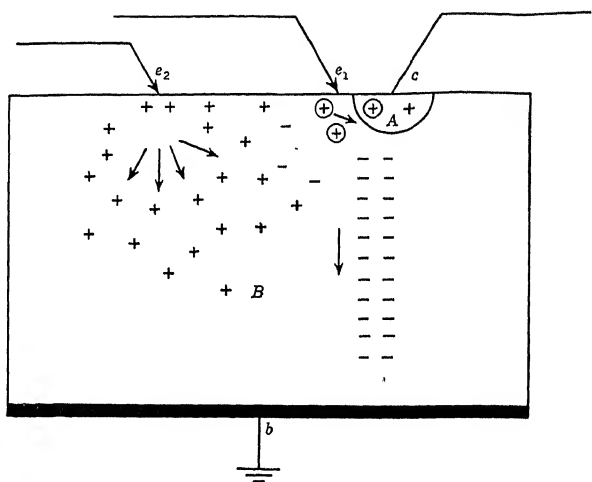
FIG. 28. The two-emitter transistor. (*Courtesy IRE.*)

injected by the second emitter are indicated by $+$. Electrons are indicated by $-$. The region near the collector where the amplifying action takes place is labeled A, and the rest of the germanium block is labeled region B. In the absence of the second emitter, holes produced by the first emitter travel to the collector region, where they form a positive space charge. This serves to attract electrons from nearby regions of the germanium block, and these electrons flow in the collector circuit.

When the second emitter is added and forward biased, then it, too, will inject holes into the germanium crystal. In the absence of the first emitter very few of these holes would last long enough (by avoiding recombination with electrons) to reach the collector. However, with the first emitter present and in operation, electrons are drawn to the collector by the concentration of holes (from the first emitter), and this tends to clear the region between the second emitter and the col-

* R. F. Rutz, A Two-emitter Transistor with High Adjustable Alpha, *Proc. IRE*, July, 1955.

lector of enough electrons to enable many of the second-emitter holes to reach the collector. This addition of more holes around the collector serves to attract even more electrons to the collector region, with the result that more collector current will flow for each potential fluctuation at emitter No. 1.

Figure 29 shows the relationship between α and the current drawn by the second emitter. The greater this current, the higher the α value.
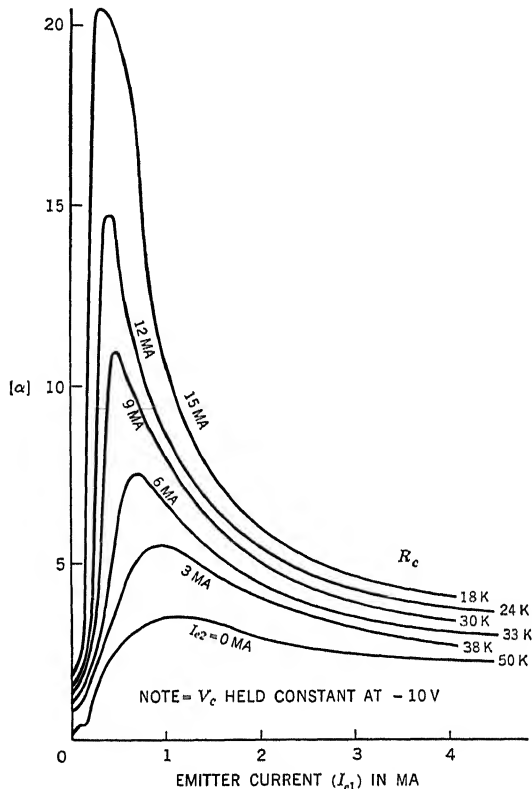
FIG. 29. α vs. I_{e1}, for various values of second-emitter current for a transistor in which the second emitter is spaced far from the collector. R_c is the load resistor in the collector circuit. (*Courtesy IRE.*)

By inserting a variable resistance in the second-emitter circuit, we can vary the value of α to suit whatever purpose we have in mind. For example, the second emitter could be employed to control or modulate the gain of an amplifier.

A THYRATRON TRANSISTOR *

A transistor recently developed in the IBM Research Laboratory has been used to replace a thyratron tube in many circuit applications. Structurally, this transistor is somewhat of a cross between a junction and point-contact transistor. The base and emitter sections possess a form very similar to that employed in the conventional junction transistor. The collector, however, makes a point contact with the base.

A detailed picture of the structure of this transistor is shown in Figs. 30 and 31. The body or base of the transistor is a thin wafer of N-type
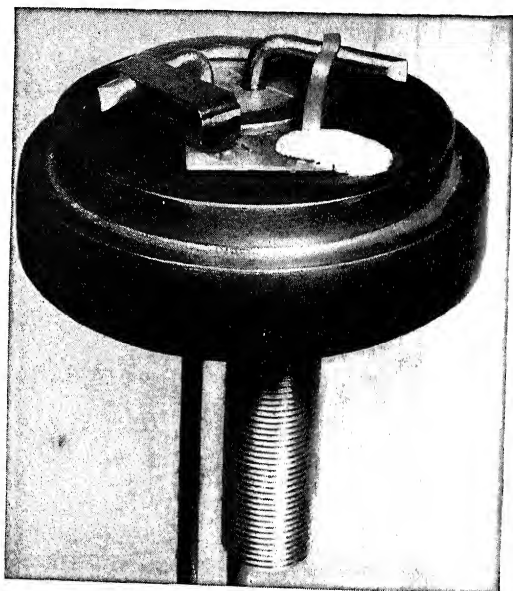
FIG. 30. The IBM transistor that exhibits thyratronlike characteristics. (*Courtesy IBM.*)

germanium. A circular P region about 40 mils in diameter is formed on the bottom of the wafer by alloying with indium. This region is attached to a copper heat sink by indium solder. The base tab is a 5-mil nickel strip with a 60-mil hole which is soldered to the upper face of the germanium wafer so that the hole in the base tab is concentric with the P region. The collector is a pointed phosphor-bronze wire or

* A. W. Berger and R. F. Rutz, A New Transistor with Thyratron-like Characteristics, a paper presented at the 1955 AIEE-IRE Electronic Components Conference at Los Angeles, Calif.

strip which is electrically "formed" in the same way that point-contact transistor collectors are formed. In some models, provision is made in the cap to allow light to be focused on the N-type germanium beneath the hole in the base tab. This allows the transistor to be turned on, or
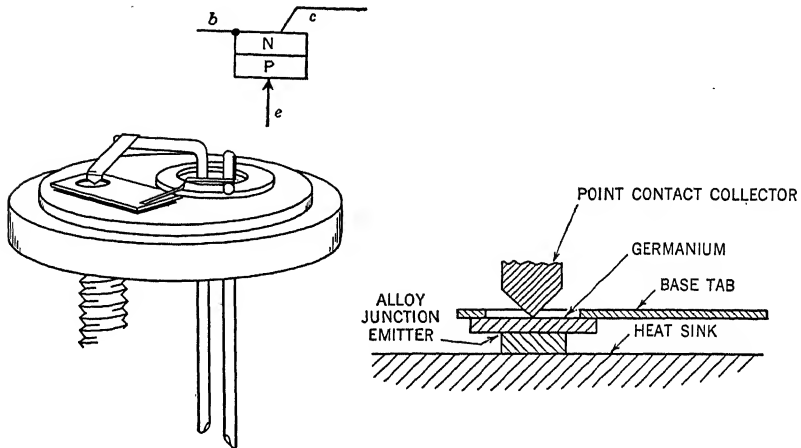
FIG. 31. The IBM x-4 thyratron transistor. The symbol IBM uses to designate this transistor is shown at the top of the illustration.

"fired," by means of a light beam. The large copper disk to which the emitter is connected has a stud bolt incorporated in it so that it can be bolted to the mounting chassis which acts as a heat sink for the unit.

In order to understand how this transistor functions, let us connect it with the emitter grounded, a negative voltage applied to the collector, and a positive voltage applied to the base. The circuit is shown in Fig. 32. For this explanation, a positive base voltage of 3 volts is assumed and a negative collector voltage of 20 volts.

Under these conditions, the base-emitter circuit is reverse-biased to the extent of the base voltage, since the emitter itself is grounded. Between the base and collector we have a much higher reverse bias,

FIG. 32. Thyratron transistor with biasing voltage.

here totaling 20 + 3, or 23 volts. It would thus appear, at first glance, that nothing would happen. Actually, this is not true, because the N-type base region is formed so that it possesses a fair amount of holes. These are in the minority, to be sure, but they exist nonetheless. By the same

token, the P region formed just under the pointed phosphor-bronze wire of the collector also possesses a number of electrons, although here, again, these are in the minority. Hence, when 23 volts is applied between base and collector, a current will flow through these two sections. This current is comparable to the I_{co} current that flows in the collector circuit of a triode junction transistor. However, the current in the transistor thyratron is much larger than the I_{co} of a conventional transistor because of the impurity "doping" of the base section.

The current consists of holes in the base which are attracted to the negative collector. When these holes arrive at the collector, they combine with the electrons residing in this P region. At the instant that this combination occurs, an equivalent number of electrons are withdrawn from the base, and these flow into the positive terminal of the base battery. This electron withdrawal creates holes which then progress to the collector.

In the external circuit, batteries B_1 and B_2 are effectively in series aiding and the electron flow is from the base through B_1 and B_2 to the collector.

While this action is occurring, the emitter is prevented from conducting by the reverse base-emitter bias. However, as we increase the collector voltage, the current increases through the base-collector circuit until the base is unable to supply any additional holes. At this point, holes are drawn from the emitter, since it is a P region. The new path, representing a break-through of the reverse-biased base-emitter junction, brings more of the collector-to-emitter voltage to the emitter junction. And this negative voltage, attracting the holes in the emitter section, acts to counteract the base-emitter reverse bias. As a result of this action, more emitter current flows to the collector, which serves to reduce further the resistance between emitter and collector and bring more of the collector voltage to the emitter junction. This, in turn, produces a larger emitter current.

The effect here is one of "snowballing," or feeding on itself, so that once started, it progresses extremely fast. With a large current flowing between emitter and collector, the voltage between these two elements drops down to about 2½ volts. The remainder of the collector voltage now appears across whatever load is employed in the collector output circuit. This might be a resistor or, more likely, a relay.

In order to bring the transistor back to the low-current state, that is, to turn off the current through the load, the base current must be returned to its initial value and the collector voltage momentarily reduced to a very low value. Here the similarity to the vacuum-tube thyratron is quite marked.

With the foregoing understanding of the physical operation of this transistor thyratron, let us examine the characteristic curves of this device (see Fig. 33). For example, when the base current is set at 2 ma, then the behavior indicated by the curve labeled $I_b = 2$ ma takes place. That is, no current flows through the emitter until the collector voltage reaches the neighborhood of -30 volts. At this point the break-through occurs and the collector current is greatly enhanced by the
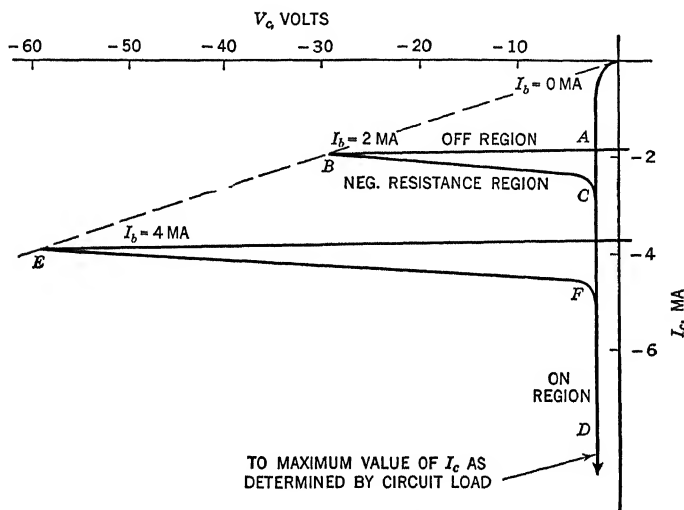
Fig. 33. Characteristic curves of IBM thyratron transistor.

addition of the large emitter current. From the curve, $I_b = 2$ ma, the collector resistance drops down to a low value, and the collector current rises sharply. The drop in collector resistance is evidenced by the drop in the curve between points BC. At point C, the collector current increases sharply because it moves along the vertical line CD. This line extends into the high-current region.

If we place a larger positive voltage on the base, the base-to-collector current will rise correspondingly. Let us assume that this rise is to 4 ma. Note that now the collector voltage must reach almost -60 volts before the current break-through from the emitter occurs. (The current avalanche from the emitter under these conditions is indicated by the $I_b = 4$ ma curve between points EFD.) The reason for this behavior is easy to see. If the base is made more positive, it means that the reverse bias between base and emitter is greater. It means also that with the base providing more current (i.e., holes), the collector voltage will be able to go to a higher value before the base supply of holes is depleted.

It is also possible to obtain a large emitter-collector flow of current when the base current is zero; i.e., when the base circuit is open. Under these conditions, the collector current will rise in step with collector voltage up to a value of approximately −1.5 volts. This flow of current stems from emitter holes which are attracted by the negative collector voltage. When these holes arrive at the collector, they act to break down the barrier so that more of the collector-to-emitter voltage appears across the emitter junction, causing a still greater hole flow. At a collector voltage of about −1.5 volts, the collector current rises rapidly to a value determined by the capacitance of the thyratron and the resistance in the collector output circuit. To interrupt this action, the collector circuit must be opened.

Thus, thyratron behavior can be obtained even in the absence of any base voltage. However, in most applications, some means of control (by triggering) is desired, and the base circuit is employed.

The dashed line in Fig. 33 represents the boundary of the turn-around points for the two curves shown and for all intermediate curves, those obtained when the base current is between 2 and 4 ma. By extending the line down to the origin and above $I_b = 4$ ma, we can predict the behavior for a wide variety of base-current conditions. Note, then, that by regulating the base current via its voltage, we can alter the instant of "firing" and thus control the behavior of this device.

The limit on the current that can be drawn through the transistor in the "on" state is determined to a great extent by the rate at which heat can be removed from the structure. This is because the high temperatures generated locally at the collector point by high currents tend to overform the point contact. In the present state of development, this transistor can safely handle 100 ma. Experimental models have been made which have switched currents as high as 15 amp for very short times. Repeated pulses of such high amplitude tend to deteriorate the characteristics of the transistor.

Light rays can be used to switch the transistor from the "off" state to the "on" state when it is operated in the grounded-emitter thyratron circuit connection. This is accomplished by allowing light of wavelength shorter than 1.5 microns to impinge upon the N-type region of the semiconductor body. A lens or transparent window in the cap of the transistor may be used so that light can be focused into the hole in the base tab. Holes formed by absorption of the light energy by the atoms of the germanium crystal structure may trigger the turn-on process directly and most efficiently by diffusing to the collector. Holes may also initiate turn-on indirectly, by diffusing to the emitter. In the latter case the holes enter the emitter, since there is no barrier

for them. This lowers the potential of the N region until the emitter junction becomes forward biased under the negative collector. The holes which are injected there reach the collector and initiate turn-on.

THE UNIPOLAR FIELD-EFFECT TRANSISTOR

Still another form of transistor which is being investigated carefully and which apparently possesses sufficient commercial possibilities to warrant pilot-plant production is the field-effect transistor. Not only does the construction of this unit differ considerably from all previous transistors, but in it we encounter a new operational method of approach as well.

The basic structure of a field-effect transistor is shown in Fig. 34. The body of the device consists of a rectangular block of N-type germanium.
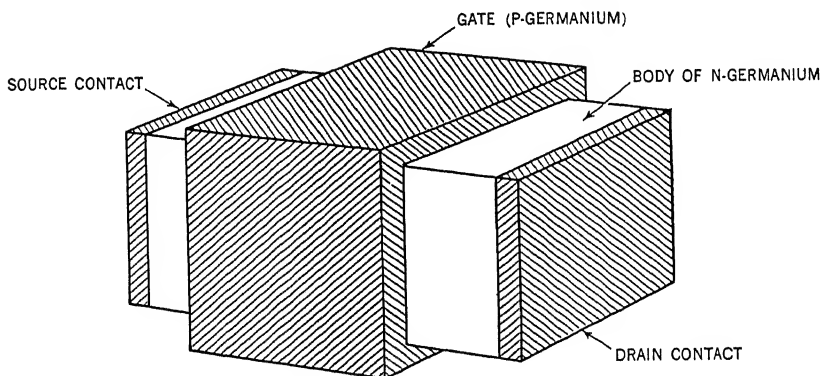
FIG. 34. Basic construction of field-effect transistor.

Around the center of this block, a continuous P-type junction is formed. In addition, there are two ohmic connections, one at each end of the N-type block. These contacts serve the purpose of bringing externally applied voltages (and signals) in contact with the unit.

In previous transistors, the three electrodes were always known as base, emitter, and collector. In the present instance, entirely new names are employed. The P section that completely circumvents the central block is called the "gate." The ohmic contact at the left is known as the "source," while its counterpart at the right is called the "drain." The reason for the choice of these particular designations will become clearer as we examine the operation of this device.

To start, let us apply a voltage between the source and drain elec-

trodes with the drain terminal made positive with respect to the source. This is shown in Fig. 35. At the same time, let us connect the P-type gate to the source terminal. Under these conditions the gate is said to possess zero potential, the source electrode serving as the reference point for the entire unit.
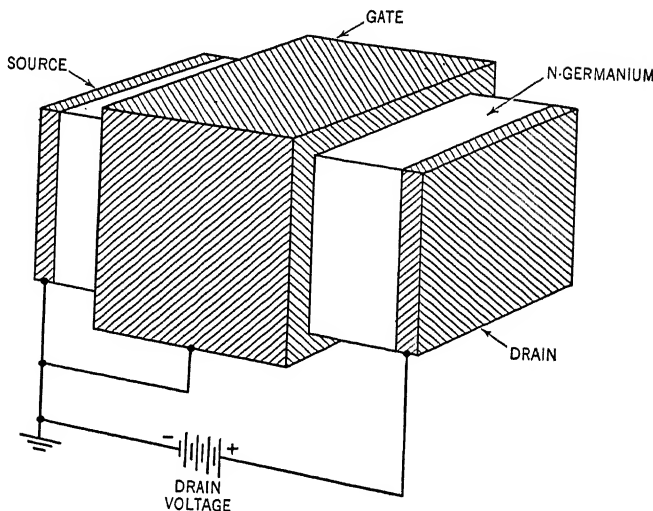
FIG. 35. Voltages applied to field-effect transistor. Gate is at same potential as source, while drain is positive with respect to source.

Electrons will travel from the source to the more positive drain electrode when a voltage is applied to these end terminals. Since a definite potential is being applied across the ends of the N-germanium block and since this material possesses a certain amount of resistance, the applied voltage will be distributed equally along the body of the N germanium, from the source to the drain. In the present arrangement, the potential will become progressively more positive as we travel from the source to the drain. (If the reader has any difficulty visualizing this distributed voltage drop, let him substitute a resistor for the germanium block. A point on this resistor which is closer to the positive end of the battery will be more positive than any point along the resistor to the left. The same situation holds for the germanium crystal.)

Now consider the gate. This forms a PN junction with the germanium block over the area in which the two are in contact. The end of the gate nearest the source will find the least amount of potential difference between it and the body of the germanium block just under-

neath. This is at point *A* in Fig. 36, and the reason is quite simple. The gate itself is at the same potential as the source, since the two are externally directly connected. Inside the body of the germanium block, however, at point *A*, there exists a small positive potential (with respect to the source) because of the above-mentioned voltage drop. This positive potential at *A* repels the holes in the end of the P-type gate just above it and also exerts an attractive force on the electrons in the germanium block. Thus, a small reverse bias is present here.
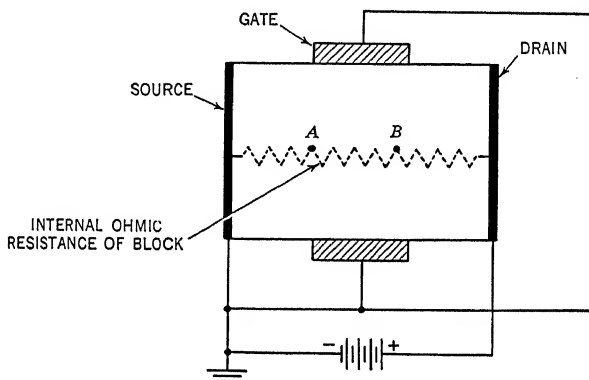
FIG. 36. A side view of field-effect transistor. The internal ohmic resistance of the germanium block is represented by the dotted resistor. Owing to the voltage drop across this resistance, point *B* is more positive than point *A*.

As we progress farther down the block, the positive potential (with respect to the gate) increases, making the reverse bias across the PN junction even greater. Thus, there is no tendency on the part of the electrons in the block to flow to the gate or for the holes in the gate to cross the junction and move into the block.

However, holes do exist in the block. These come from three sources: (1) They may be thermally generated in the body of the semiconductor, (2) they may be developed at the surfaces of this block, or (3) they may come from the two end contacts, the source and drain metal electrodes. In any event, a certain number of holes exist in the N-type germanium, although the donor electrons exceed these by ratios as high as 10 to 1 or more.

Under the repelling effect of the positive voltage drop along the semiconductor body and the attractive force of the more negative gate, holes in the semiconductor will be drawn up to the gate. The number of holes which are drawn from any section of the block will be governed by the positive potential present in that area. Thus, more holes

will be drawn from the right-hand section of the block than the left-hand section.

Now consider the P-type gate. It will possess a number of free electrons, possibly for some of the same reasons that the N-type body possesses holes. And these electrons will be repelled by the negative potential of the gate and attracted by the more positive potentials within the germanium block. Hence, there will be a movement of electrons out of the gate and into the block, with the greatest number of electrons leaving the gate at the right-hand side of the germanium body.

One result of this redistribution of charge is to make the PN junction more reverse-biased than before. Another result is to increase the negative space charge in the germanium block, with the concentration greatest at the right. The actual space-charge distribution is shown in Fig. 37. It rises to a maximum at the right-hand edge of the P gate
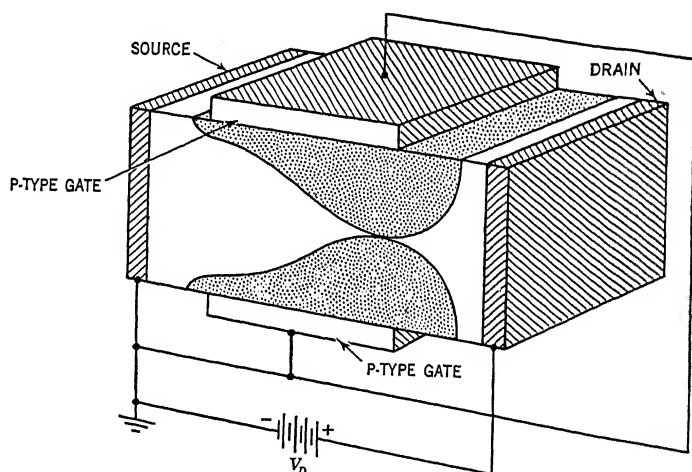
Fig. 37. The shape of the space-charge distribution within the body of a field-effect transistor. (*Courtesy IRE.*)

and then decreases fairly rapidly. This space charge exerts a repelling force on those electrons traveling from the source to the drain electrodes because of the externally applied potential. What it actually does is channel, or direct, the current flow into the regions between the concentrated space charge. These regions are shown in white in Fig. 37. The dotted area represents the negative space charge.

. As the drain voltage is increased, the current flow through the semiconductor will rise until the drain voltage reaches a certain critical limiting value which is referred to as the pinch-off voltage. Beyond

this point, no further increases in drain current will result as the drain voltage is made greater. The only effect of higher voltages is to alter the shape of the channel through which the electrons flow.

Thus far, the gate has been held at the same potential as the source. If, now, we make the gate negative with respect to the source terminal by the insertion of an additional negative voltage, then the amount of external voltage needed between source and drain in order to reach the constant drain current value will be much less. This is because the negative gate voltage aids the space charge in the germanium body to narrow the channel of the current. Eventually, if the negative potential of the gate is made high enough, current flow through the device will be halted completely.

The foregoing behavior is depicted by the curves in Fig. 38. Maximum saturation current flows when V_G (the gate voltage) is zero with
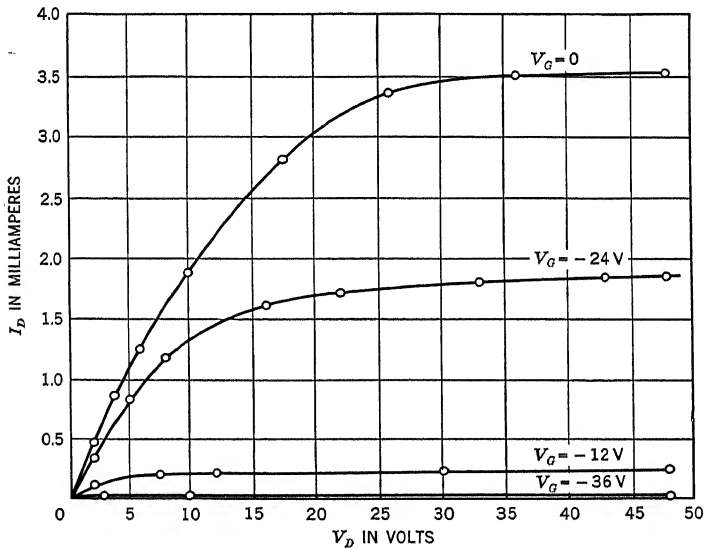
FIG. 38. The characteristic curves of a field-effect transistor. (*Courtesy IRE.*)

respect to source. For each successively lower current curve, the negative bias on the gate becomes greater. When the gate potential is equal to the pinch-off voltage, the amount of current flowing through the semiconductor is very small.

The circuit in Fig. 39 is similar to that of Fig. 35 with the addition of a signal in series with the gate bias battery. As the signal varies, it will vary the total voltage applied to the gate. When the signal is negative, the gate will become more negative and serve to reduce the flow

of drain current. On the next half cycle, when the signal goes positive, the over-all gate voltage will be made less negative. This will reduce the space charge in the body of the semiconductor, and the drain current will rise. In short, a small voltage variation at the gate will produce a sizable current variation in the germanium crystal. In a vacuum tube, this characteristic is labeled transconductance and is responsible for the amplification which is obtained. Obviously the same results should be possible in the field-effect transistor, enabling us to use this device to achieve signal amplification.
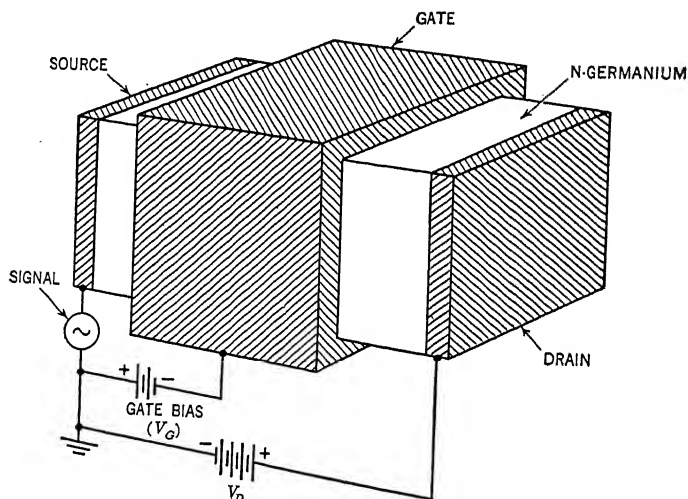
Fig. 39. The field-effect transistor with a negative gate bias voltage V_G. Also shown is the point where a signal would be injected.

The similarity between the field-effect transistor and triode vacuum tube is quite marked. In a vacuum tube, the grid potential regulates the space charge existing between cathode and plate and, by this control, determines the extent of plate current flow. In the field-effect transistor, the polarity of the gate governs the intensity of the negative space charge existing in the N material and, through this, the amplitude of the current flowing from source to drain.

Another interesting feature of this transistor is the fact that essentially only one type of carrier, here electrons,* is involved in the

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* A field-effect transistor could be constructed using a P-type main body and an N-type gate. Battery potentials would have to be reversed, and the current in the source-drain channel would be carried by holes. Similar results, however, would be obtained.

process. This is in sharp distinction to the conventional transistor, where both types of carriers play a role. Hence, this device is called a unipolar transistor. It also results in a very significant difference in the way amplification is achieved. In the conventional triode transistor, the carriers must travel from the emitter through the base to the collector. This makes carrier transit time an important factor in determining frequency response. In the field-effect transistor, the signal at the gate serves to modulate the drain current and in this way produce the signal variations in the drain output circuit. Carriers do not have to transport the signal from the gate to the drain; hence carrier transit time is not involved. We do not even have to worry about transit time from source to drain, because the signal voltage at the gate merely expands or contracts the current stream. It does not alter its rate of travel. This does not mean that the field-effect transistor is without frequency limitation. It is not, because there are certain shunting capacitances to be dealt with plus the variation of transconductance with frequency and other effects. But transit time does not possess the significance here that it does in other transistor structures.

Operating frequencies of 140 Mc have been obtained with experimental field-effect transistors. Another important feature of these devices is their high input and output impedances. In this respect they resemble pentodes. However, the units do possess a fairly high noise figure, which means that they are not suitable for low-power applications. They are also useful in various types of oscillators, such as multivibrators, Colpitts oscillators, and relaxation circuits.

SILICON TRANSISTORS

The emphasis in all the preceding discussion has been on germanium as the semiconductor material from which transistors were made. It is also possible to employ silicon as the fundamental building block for a transistor, and this has indeed been done. Silicon is suitable for diode and transistor operation because its physical properties closely parallel those of germanium. Thus, silicon is a semiconductor with four valence electrons, and in the solid state, it will form a cubic crystal lattice in which the various atoms are held together by the same mechanism of covalent bonds. It is possible to replace some of these atoms by impurities, of either the donor or acceptor variety, and form N-type or P-type silicon. By combining suitable P- and N-type sections of silicon, rectifier diodes or complete transistors can be fabricated.

In view of the physical similarities between these two elements, it is only natural to investigate both substances to determine which is

best suited for transistor operation. Actually, as we shall see, there are certain advantages and disadvantages to either type, and it becomes a matter of choosing the unit that possesses the greatest suitability for a specific application.

Of the two substances, silicon is far more abundant in nature than germanium. As a matter of fact, silicon compounds form over 85 per cent of the earth's crust. All sand, for example, is silicon dioxide, while additional silicon compounds are present in many rocks. Unfortunately, silicon is never found in the free state, and in order to utilize it for transistor manufacture, extensive separation and refining methods must be employed. This represents a major obstacle, because silicon is not easily reduced to the pure state. It is an extremely difficult substance to melt or purify; its processing requires higher powered, complex, and expensive furnaces. Furthermore, the methods which have been successful to date are more difficult to adapt to mass production, something which is absolutely necessary if silicon transistors are to possess commercial usefulness.

One of the most important advantages of silicon, which is in large measure responsible for much of the attention being devoted to this element, is the low collector saturation current I_{co} which silicon transistors exhibit. It will be recalled that this particular characteristic in germanium transistors was extremely sensitive to temperature variations and that unless the proper safeguards were taken, not only did instability result but the rise in I_{co} with temperature could feed on itself and lead to the eventual destruction of the transistor.

Table 1 contains a comparison between what might be termed typical junction transistor characteristics for both silicon and germanium, and the great disparity in I_{co} values is readily observed. The ratio might be anywhere in the range from 100:1 to 500:1. The rate of increase in I_{co} with temperature is about equal for both types of transistors. However, since the value of I_{co} for silicon is so extremely small at room temperature, the unit can be used at much higher temperatures before it becomes troublesome.

Another property in which silicon excels is in its collector resistance r_c. This value is higher than the comparable collector resistance of germanium transistors. Thus, as we raise the operating temperature, r_c in both types of transistors will decrease, but since this quantity started from a higher value in silicon, it is possible to go to higher temperatures before r_c becomes too small to use. When the behavior of I_{co} and r_c is considered, it is seen why silicon transistors possess higher maximum dissipations and why they are useful as high as 150°C.

A major reason for these characteristics is directly attributed to the

Table 1. Comparative Characteristics of Silicon and Germanium Transistors

	Symbol	Silicon Grown	Germanium Grown	Germanium Alloy
Collector:				
Voltage (maximum), volts	$V_{c\ max}$	40	40	25
Dissipation (maximum), mw	....	150	50	50
Cut-off current, μa	I_{co}	0.02	2	10
Capacitance, $\mu\mu$f	C_c	7	14	40
Conductance—parallel, μmhos	g_c	0.3	0.2	1.0
Emitter:				
Current (minimum usable), ma	I_e	1	0.01	0.1
Reverse voltage (maximum), volts	$V_{e\ max}$	2	10	5
Bias voltage, mv	V_e	500	160	160
Resistance, ohms	r_e	100	25	25
Base, resistance, ohms	r'_b	500	150	300
Gain:				
Power, db	G_o	35	47	40
Current	B	26	35	40

Courtesy *Electronic Design* magazine.

larger energy gap that exists between the valence band and the conduction band in silicon atoms. It will be recalled, from Chap. 1, that in order for an electron to jump from the valence band to the conduction band, a certain amount of energy is required. In silicon, more energy is needed to accomplish this jump than in germanium. This same factor also explains why more bias voltage is needed to produce a certain current in the emitter. This is indicated in Table 1 as well as the fact that the base resistance is higher in silicon transistors. When the unit is employed as a grounded emitter, the higher base resistance requires more driving power from the previous stage.

Current and power gains of silicon units are each lower than corresponding germanium transistors. The mobility of electrons in silicon is about one-seventh that of germanium. This tends to work against the frequency response of silicon transistors. However, there are other factors that have to be taken into consideration when considering frequency response. For example, collector capacitance C_c is a very important frequency-determining factor (as we have already seen in this chapter), and in silicon units this value is much lower than in germanium transistors. Another compensating factor is that higher collector voltages may be employed with silicon transistors; this serves to

decrease further the effective value of C_c, thus aiding the frequency response.

At the present time, most of the silicon transistors commercially available are of the NPN variety and are fabricated by the grown junction process. Work, however, is progressing on fused junction units, and if suitable mass-production techniques can be developed, fused transistors will probably be more widely used. Transistors produced by the latter method possess certain advantages over the grown units; these include lower base resistance, greater electrical symmetry for use in two-way (i.e., bilateral) applications, and a higher emitter back breakdown voltage.* Furthermore, the fusion process yields more transistors than the grown method, using the same amount of pure silicon crystal.

In January, 1956, the Bell Telephone Laboratories at Murray Hill, N.J., revealed that silicon transistors had been fabricated using a gaseous diffusion process that yielded base layers only 0.15 mil thick. This, in turn, produced alpha-cutoff frequencies from 100 to 120 Mc. The same gaseous diffusion process, applied to germanium transistors, produced base regions 0.04 mil thick. Alpha-cutoff frequencies of these latter units ranged from 400 to 600 Mc.†

In one variation of this process, bars of P-type germanium are cut to the desired dimensions, then lapped and polished. After a slight etch, the bars are washed in deionized water and placed in a vacuum oven for the diffusion of an N-type impurity into the surface. In the present instance, arsenic-doped germanium is used as the source of the N-type impurity. The oven is then heated for the proper length of time, and the arsenic diffuses into the P-germanium bar. In this way, the N-type base is formed.

For the next step, the bar is masked and a film of aluminum is evaporated onto it. The bar is heated to alloy the aluminum, thus forming the emitter region. Thus, the base is formed by gaseous diffusion and the emitter by alloying.

With silicon, an extension of the gaseous method is employed to form both the base and the emitter. This is known as the double-diffusion process and is based on the fact that in silicon, the diffusion coefficient of acceptor impurities, such as aluminum, is ten to a hundred times that of a donor impurity, such as antimony. Thus, by the

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* Gudmendsen *et al.*, Recent Developments in Silicon Fusion Transistors, *IRE Trans.*, PCED 2, no. 1, pp. 74–81, January, 1955.

† M. Tannenbaum and D. E. Thomas, Diffused Emitter and Base Silicon Transistors, and C. A. Lee, A High-frequency Diffused Base Germanium Transistor, both in *Bell System Tech. J.*, January, 1956.

simultaneous diffusion of selected donor and acceptor impurities into N-type silicon, an NPN structure will result. The first N layer forms because the surface concentration of the donor is greater than that of the acceptor. The P layer is produced because the acceptor diffuses faster than the donor and gets ahead of it. The final N region is simply the original background doping of the N-type silicon sample. It has been possible to produce NPN structures by the simultaneous diffusion of several combinations of donors and acceptors. Often, however, the diffusion coefficients and surface concentrations of the donors and acceptors are such that optimum layer thicknesses are not produced by simultaneous diffusion. In this case, one of the impurities is started ahead of the other in a prior diffusion, and then the other impurity is diffused in a second operation.

TRANSISTOR COMPONENTS

Before we close this chapter, some mention should be made of the miniature and subminiature components which, in many instances, have been developed to take advantage of the space saving afforded by the use of transistors (see Fig. 40). It would obviously be wasteful of space to use transistors, which are of the order of $\frac{3}{16}$ in. square, with normal-size components. In addition, the lower current and voltage requirements of transistors tend to simplify greatly the problems which are encountered when component miniaturization is undertaken normally.

To appreciate some of the obstacles which must be overcome when a component is made more compact, consider the transformer for example. A transformer generates a certain amount of heat as a result of the current flowing through its windings. This heat must be dissipated, but as we work toward miniaturization, we reduce the available surface radiating area. Furthermore, to attain a smaller volume in the first place, smaller size wire must be employed in the windings, and this, in turn, possesses a higher resistance so that more heat is generated by the current flowing through the wires.

Both of the foregoing factors force the transformer to operate at a higher temperature, and if suitable insulating materials are not developed, component failure will be high.

Temperature also enters the picture in still another way. Over-all reduction of equipment, a direct consequence of component miniaturization, means that the amount of heat generated per unit volume will be higher than in conventionally sized equipment, where the spacing between components can be made much greater. This leads
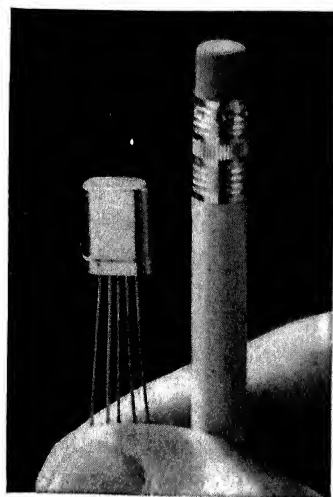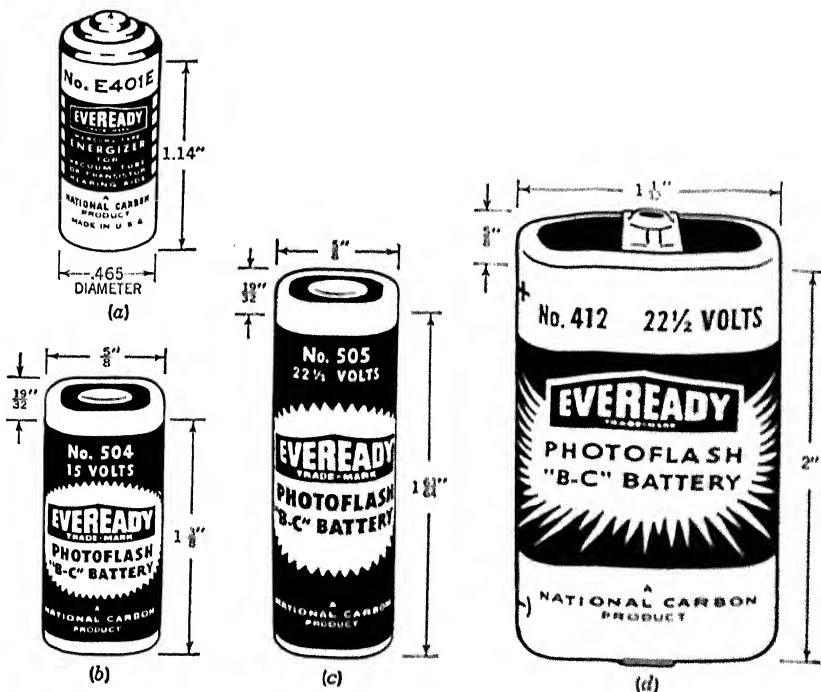
FIG. 40. Some illustrations of miniature components developed for use with transistors and small tubes. (a) through (d) Four different battery sizes and voltages. (e) Shock-resistant relay developed by a subsidiary of the Elgin National Watch Company. (f) Small trimmer capacitor.

to a higher ambient temperature, and this factor, added to the increased heat generated within each component itself, further aggravates the demands made upon the materials used.

The solution resided in the development of new substances possessing greater heat-resistant properties than heretofore possible. In transformers, silicon-impregnated Fiberglas, Mylar, and adhesive Teflon tapes are used extensively to provide improved insulation between the various layers and windings. The shapes of cores used fall generally into the toroid or flat laminated categories. Tape-wound toroids are a most convenient way of obtaining a miniature core using thinner material; air gaps are minimized with this construction, permitting utilization of almost the full permeability of the material. When flat laminations are employed, they generally possess an E or I configuration.

Cores are fabricated from such high-permeability materials as Ferroxcube, grain-oriented Hipersil steel, Moly-Permalloy powder, or grain-oriented Silectron steel. Formvar-type wire coatings, bobbin windings (in contrast to the layer windings common in larger transformers), and improved production techniques, especially in the handling of the very fine wire used, all have combined to permit the evolution of transformers which are truly miniature in size (see Fig. 8, Chap. 4).

In another component, fixed capacitors (Fig. 41), the problem of miniaturization is being overcome in a number of ways. For nonelectrolytic capacitors, generally those less than 1 μf in value, extensive use is being made of plastic, impregnated paper, and ceramic dielectrics. Desirable characteristics in a dielectric are high insulation resistance, relatively low temperature coefficient capacitance (i.e., small change in capacitance with temperature), the ability to function satisfactorily over a wide range of temperatures, and a high dielectric constant. (Few substances possess all these characteristics, and the end product is usually a compromise.)

In plastic dielectrics, wide use is being made of Mylar, a product of E. I. du Pont de Nemours & Company. This substance, which is chemically a polyester, possesses a high resistivity to heat and excellent mechanical strength. In thin films it is frequently impregnated with silicon, mineral oil, or polystyrene. Dielectric constant of Mylar is around 3, and it remains fairly constant with frequency.

When paper dielectrics are employed, the paper is frequently impregnated with vegetable or mineral oils or with a synthetic compound such as the recently developed Permafil (General Electric Company). Metallized paper capacitors are also rather widely used. In these units,
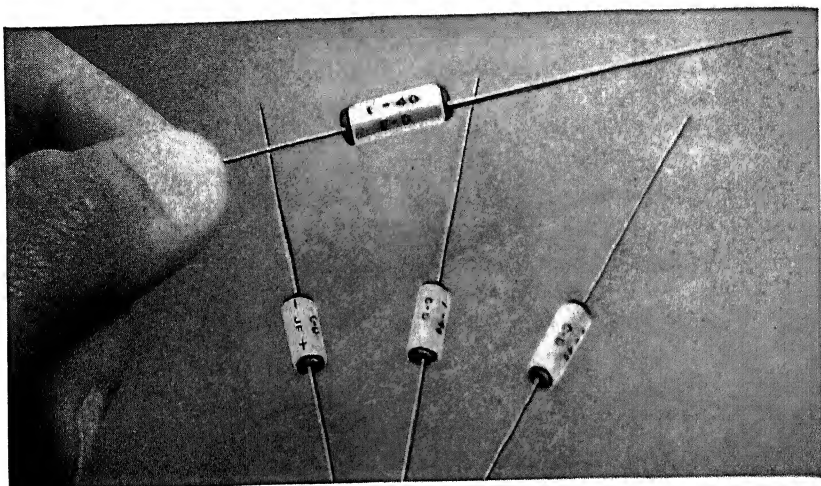
(a)
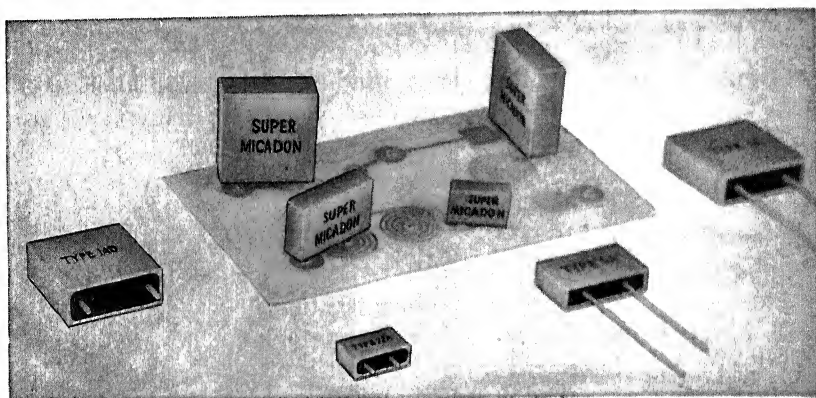
(b)
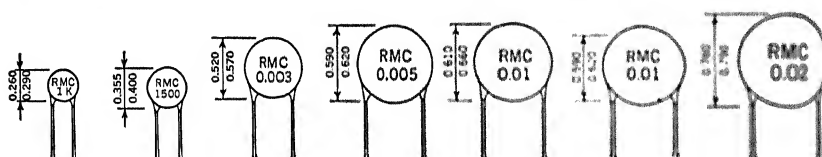
(c)

Fig. 41. Several illustrations of miniature capacitors employed in transistor circuits. (a) Tantalum-foil electrolytic capacitors available with capacitance values up to 8 μf. (b) Mica capacitors. (c) Ceramic capacitors. The values marked on these units are indicative of their general size.

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the conventional separate layers of metallic foil are replaced with an extremely thin film of metal which is deposited directly on a lacquered surface of the paper dielectric by a high-vacuum vaporizing process. This lacquer coating considerably improves the dielectric strength and insulation resistance of the paper.

Within recent years, a wide variety of ceramic dielectrics have appeared (as in the Erie Ceramicons) which, because of their high dielectric constant, permit the fabrication of fairly high-valued capacitors in small volumes. One disadvantage of some of the very high-dielectric-constant substances is their sensitivity to temperature. This means that the capacitance value can change markedly as the equipment warms up. However, in many applications, such as bypassing and coupling, considerable variation is tolerable. In fully transistorized equipment, where there are no vacuum tubes to generate large quantities of heat, this temperature dependence does not present any undue difficulties.

The trend toward miniature fixed capacitors of the type just described was established before transistors became commercially available. However, the story of miniature electrolytic capacitors is entirely different. For transistor operation, bypass capacitor values in the microfarad region are required because of the low impedances inherent in such circuits. Coupling capacitors of 2 to 10 μf are not uncommon, as we noted in earlier chapters, and for bypass functions, capacitance to 50 μf is employed. Fortunately, the voltages used in transistor circuits are extraordinarily low, and this does help to simplify the problem.

One dielectric which is being used widely in the fabrication of miniature electrolytic capacitors is tantalum. The tantalum anode is in the form of a wire which is completely surrounded by a porous, absorbent sleeve, effectively insulating this section from the base. A neutral electrolyte is used whose properties are so chosen that these capacitors show excellent capacitance stability and power characteristics over the temperature range -20 to $+55°C$.

The tantalum anode and the electrolyte are hermetically sealed into a solid silver tubular case which serves as the cathode. Terminal leads are of solid tinned copper. Dimensions of a typical unit designed to possess a capacitance of 8 μf at 4 volts (direct current) are ⅜ in. in diameter by ½ in. long.

Considerable ingenuity is also being shown in developing miniature variable capacitors for use as tuning elements in highly compact portable receivers. One illustration of a subminiature tuning capacitor is shown in Fig. 42. Over-all dimensions, exclusive of shaft, are 1¹⁄₁₆ by

$1\frac{3}{16}$ by $1\frac{1}{16}$ in. Capacitance range is up to 430 μf per section, with a maximum-to-minimum ratio of 10 to 1.

The high capacitance of this unit is achieved by using dielectric plates formed by fusing Teflon on copper. The dielectric plates are then mechanically coupled to a screw drive, and tuning is accomplished by moving the Teflon plates in or out of the capacitor plates. Composition of the latter is 18 per cent nickel and 82 per cent silver.
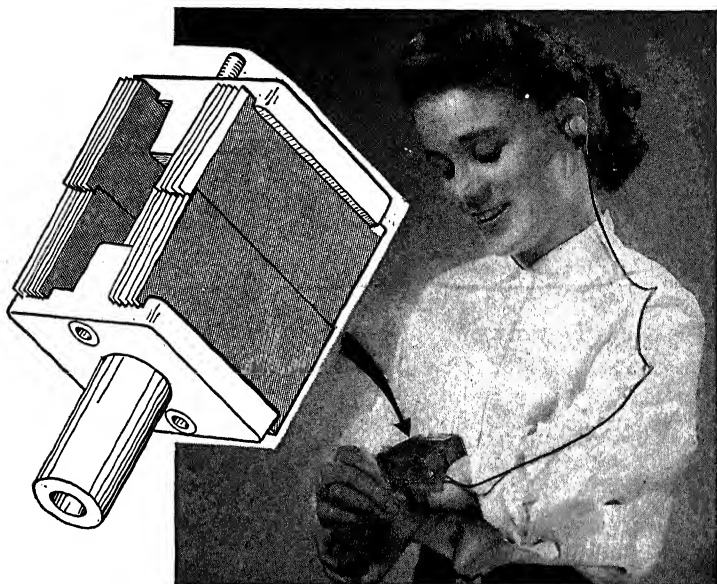
Fig. 42. A subminiature tuning capacitor and an illustration of its application in a transistorized wrist radio.

The fabrication of resistors, particularly those designed specifically for transistor circuits, is also made easier by the low voltage and currents which are found in these circuits. Wattage requirements are of little importance and in most instances can be ignored. To achieve the necessary resistance in a small space, techniques have been developed enabling certain resistive coatings to be deposited on glass and ceramic bases. The unit is then encased in a plastic jacket that affords protection against moisture.

Essentially the same story of the development of newer materials can be told of most other components which are today being used in electronic circuits. Familiar substances are being modified to acquire more desirable properties or else are being replaced completely by newer materials. And much of the credit for these developments must be

given to the physical chemists who are pioneering these "miracle" materials and to the mechanical engineers who are adapting them to mass production.

QUESTIONS

1. Why are phototransistors frequently more desirable than phototubes? How does the phototransistor of Fig. 1 operate?

2. Explain the reason for the shape of the curve in Fig. 2.

3. Why does the response of a phototransistor depend upon the wavelength of the incident light?

4. How does the phototransistor in Fig. 6 function? Show one application.

5. What is a tetrode transistor? Show the structure of such a device, and indicate the polarity of the biasing voltage applied to each element.

6. Why does the tetrode transistor possess a wider frequency-response characteristic than a triode transistor?

7. Draw the circuit diagram of a transistor frequency converter using a tetrode transistor.

8. What advantage do we gain by increasing the width of the base section of a transistor? What offsetting disadvantage?

9. How is the frequency response affected by the manner in which carriers travel across the base section of a transistor?

10. What are the two major internal capacitances in a transistor, and how do they affect frequency response?

11. What can be done to reduce these capacitances?

12. Describe the internal structure of a PNIP transistor. How does this differ from the conventional PNP transistor?

13. How does the PNIP transistor achieve a higher frequency response?

14. Describe the operation of a PNPN transistor.

15. Why can the PNPN transistor be employed as an electronic switch? Explain.

16. What is the significance of the second emitter in the two-emitter transistor of Fig. 28?

17. Describe the operation of the two-emitter transistor.

18. In what features does the IBM thyratron transistor resemble a vacuum-tube thyratron?

19. Explain how the thyratron transistor functions.

20. What happens when the positive voltage on the base of the thyratron transistor is increased? What effect does this have on the triggering point?

21. Compare the field-effect transistor with a conventional PNP (or NPN) transistor.

22. Compare the field-effect transistor with a triode vacuum tube.

23. Why is carrier transit time not so important in the operation of a field-effect transistor as it is in a conventional PNP transistor?

24. Explain why the space charge in a field-effect transistor possesses the shape shown in Fig. 37.

25. Where is the signal applied in a field-effect transistor? How is an amplified version of this signal obtained? Draw a suitable circuit to illustrate your answer.

26. What desirable features do silicon transistors possess? What undesirable features?

27. What obstacles are encountered when a component is miniaturized?

28. Name some of the ways in which these obstacles are being overcome.

29. What precautions must a service technician observe when repairing miniaturized equipment?

CHAPTER 9

SERVICING TRANSISTOR CIRCUITS

The transistor exhibits a curious combination of ruggedness and fragility. It is, for example, far more physically rugged than even the most powerfully built vacuum tube, capable of withstanding centrifugal forces with accelerations as high as 31,000 times the force of gravity and impact tests as great as 1,900 times. These are far in excess of the forces which will completely shatter any vacuum tube. On the other hand, a transistor is a fragile device with respect to heat or to the application of d-c biasing voltages possessing the wrong polarity. It is important, then, to be familiar with the physical handling limitations of transistors, so that transistor equipment can be built or serviced with a minimum adverse effect either on the transistors themselves or on the miniature components with which they are often employed.

TOOLS

Probably the first step to take in preparing yourself for transistor work is the acquisition of the proper tools. Since transistors and their associated components are extremely small, conventional-sized tools are frequently unsuitable for effective use. In their place, the technician requires tools which, because of their own reduced size, are better able to cope with the limited space encountered in compact, miniaturized equipment. In addition to the smallest cutting pliers that can be obtained, it is suggested that two or three shapes and sizes of tweezers be acquired. These will come in handy when fine wires must be soldered (or unsoldered) in the circuit. Another useful device is a soldering aid, one end of which has a notch for gripping wires while the other end comes to a fine point for probing or cleaning away solder from small openings.

Servicemen have also found a large reading or magnifying glass to

be useful, particularly one which is mounted on a holding stand so that both hands are left free. Other tools which should be available include small- and long-shank screwdrivers having narrow blades and needle-nose pliers.

Another change required by the transistor is the use of a small, low-wattage soldering iron (or pencil) possessing a narrow point or wedge. Wattage ratings on the order of 35 to 40 watts are satisfactory; anything larger than this could damage the transistor while it is being soldered into the circuit. (The same low-wattage iron is required also for the printed circuit wiring of a transistor receiver.)

To provide the transistor with the maximum protection while it is being soldered or unsoldered, it is good practice to grasp the terminal lead tightly with long-nose pliers positioned between the transistor body and the lead end. With this arrangement, any heat traveling along the wire will be shunted away from the transistor housing. It is desirable to retain the pliers on the wire for a short time after the iron has been removed to make certain that all the heat has been dissipated. It is also good practice to provide such a heat shield when other wires are being soldered to any terminal lugs to which a transistor lead is attached.

Two helpful rules to follow are to keep the transistor leads as long as possible, consistent with the space available and the application, and to get whatever soldering that has to be done over with as quickly as possible. Helpful in this respect is 60/40 low-temperature rosin-core solder.

In some instances, transistors are constructed with leads which are stiff enough to permit plugging the transistor into a specially constructed socket (see Fig. 1). In such cases, of course, soldering is no problem, and the only precaution to observe is to remove the transistor from the socket before the soldering iron is brought into contact with any of the socket terminal lugs.

FIG. 1. A representative transistor socket.

As a final word concerning the use of any tools on transistors and their associated miniaturized components, always remember that because these units are small, their connecting wires are quite fragile. Handle these wires carefully and gently, both when the part is being installed and when it is being removed.

BATTERY POTENTIALS

Two factors combine to make transistors particularly sensitive to applied bias voltages. First, there is the fact that the emitter-base junction is biased in the forward, or low-resistance, direction and the impedance of this circuit, under these conditions, is extremely low. Any voltage in excess of the required value could easily result in so large a current that the resultant heat would permanently damage the transistor. The correct operation of a transistor—any transistor—is intimately tied in with the maintenance of its crystal lattice structure and the distribution of certain impurity atoms throughout that structure. If enough heat is generated to distort the crystal structure, the effectiveness of the transistor to function as desired is seriously undermined. This is the reason for the oft-repeated warnings against applying too much heat or permitting the unit to become too warm during operation.

The second factor that makes transistors sensitive to applied bias voltages are the extremely minute dimensions of the several elements and their very limited heat-dissipating ability. Collector current is important in this respect because this current, passing through the relatively high collector resistance, develops a certain amount of heat. If this heat, added to the ambient heat at which the transistor is operating, exceeds the maximum limits of the transistor, behavior becomes erratic. This is why the maximum collector dissipation is always specified at a definite ambient temperature. If the surrounding temperature is higher than specified, the collector dissipation rating must be reduced proportionately. This is called derating and was discussed in Chap. 3.

The maximum safe value of collector voltage is important also, since too high a value will lead to a reverse current breakdown. The voltage at which this occurs is known as the Zener voltage.

Thus, because of the foregoing limitations, the value and the polarity of any voltages applied to the circuit must be scrutinized carefully. Make certain first that you have the right voltage, then check polarity before final connection is made to the circuit. If you are at all in doubt about the latter point, check the type of transistors being employed. PNP units require negative collector voltages and positive emitter voltages, both taken with respect to the base. In NPN transistors, the reverse situation holds.

Before the battery is connected to the circuit, the various transistors should be firmly in place. Never insert or remove a transistor when voltages are present. This is designed to prevent the appearance of

surge currents which, if they are powerful enough, can permanently damage a transistor. Always remove the voltage first. If you are experimenting with a new circuit or building a transistor kit, double check all wiring before applying bias voltages. If you are doubtful about the outcome, insert a current meter in series with the collector circuit and then use a potentiometer arrangement to apply the collector voltage gradually. If the collector current begins to exceed the specified maximum, you know something is at fault.

To men who have gained all their radio and television experience on vacuum-tube circuits, all these precautions may appear somewhat excessive. However, experience has revealed that they are most definitely required. Transistors are extremely sensitive to heat, and anything that develops heat, such as current flow, must be watched with a wary eye.

Another source of potential danger lies in the signal generators which the technician uses to service radio and television systems. When a signal is injected into a transistor circuit, start with a very low amplitude signal and gradually increase the generator output until the desired indication is obtained. Never inject strong signals into a transistor circuit, particularly when this is a low-level stage. Frequently, indirect-rather than direct-coupling methods of signal injection are advisable. For example, clip the "hot" output lead from the generator across the insulated body of a nearby resistor or capacitor. The signal will then enter the circuit by radiation and capacitive coupling. This approach is widely practiced in television-receiver alignment when a marker signal must be brought into the system without swamping the sweeping signal.

It has also been suggested that signal injection can be achieved by connecting the output of the signal generator to a suitable coil and then lining up the axis of this coil with that of the input of the circuit under test. This will bring the signal into the circuit by inductive coupling. In using this method, the radiating coil should be geared to the frequency of the signal frequency, that is, a high-inductance coil for low frequencies and a low-inductance coil for high frequencies.

The sensitiveness of a transistor to surge currents should be borne in mind when a voltmeter is being used to check voltages at various points in a transistor receiver. Because of the closeness with which components are placed, it is easy for the probe tip accidentally to touch two closely spaced terminals if the technician is not exceptionally careful. This simple slip may result in battery burnout or be responsible for a current surge through the transistor as, for example, when the probe

makes simultaneous contact with the collector and emitter electrodes. Extra emphasis is placed on this precaution because of the ease with which the mistake can be made. In vacuum-tube circuits, similar slips may occasionally cause a component to burn out, although they rarely affect tubes. In a transistor circuit, the transistor is usually the weakest link, and it becomes the victim.

Along these lines, here are some meter precautions which are issued by the manufacturer of the Regency pocket radio receiver discussed in Chap. 6. Some service ohmmeters utilize circuitry which necessitates an other-than-normal battery polarity inside the meter. With instruments of this type, the red test lead has a negative potential and the black lead has a positive potential. The technician should investigate his meter to determine the polarity of its leads. This can easily be done by connecting a voltmeter across the ohmmeter test prods. When measuring circuits which are critical with regard to polarity (such as those containing electrolytic capacitors), the technician should keep in mind the polarity of the meter leads and should connect them accordingly. The positive lead, whether it is red or black, should be connected to the positive lead of the electrolytic capacitor. The transistors in this receiver (i.e., the Regency model TR-1) would not be ruined if an ohmmeter were to be connected into the circuit in the reversed polarity, but the electrolytic capacitors would give incorrect readings because they would be measured backward. It is also imperative not to use an ohms range which utilizes a battery of more than 3 volts, because the transistors can be damaged if too much voltage is applied to them.

Before we leave the subject of heat and its effect on transistors, one word might be said about the precautions to observe when positioning transistors in electronic equipment. Keep transistors clear of any component, be it tube, resistor, or transformer, which passes enough current to develop a noticeable amount of heat. The ratings specified for a transistor are always given at a certain ambient temperature, generally 25°C. For every degree above this figure, a corresponding lowering of the transistor ratings must be made, thereby effectively reducing the operating range of the unit. It might be useful to remember this when you find that transistor equipment is not operating as it should and no component is apparently at fault. Measure the ambient temperature of the enclosure where the transistor is contained. Make this measurement under the same conditions that prevail when the equipment is functioning normally, that is, with the chassis in the cabinet and all removable sections or panels in place. If you possess a

Fahrenheit thermometer, the equation for conversion to centigrade is

$$°C = \frac{5}{9}(°F - 32)$$

where C = temperature, °C
$\quad\quad F$ = temperature, °F

TRANSISTOR TESTING

In the course of servicing a receiver, occasion may arise in which it is suspected that the transistor itself is at fault. At the time of this writing there are no inexpensive transistor checkers comparable to the tube testers on the market.* This leaves the service technician with two alternatives: Either he can substitute another unit known or believed to be good, or he can build his own transistor tester. For the latter, a simple circuit is shown in Fig. 2. With an a-c vacuum-tube voltmeter, measure
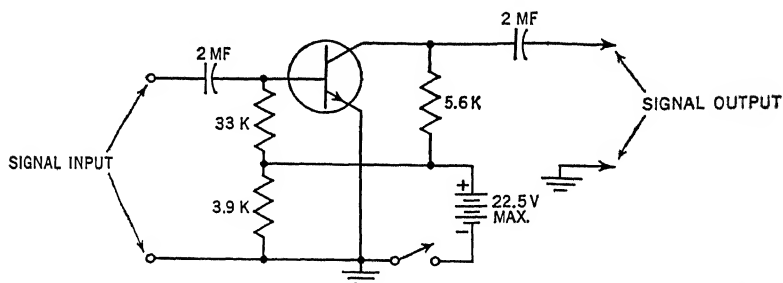
Fig. 2. Circuit for testing transistors. Connections are shown for an NPN-type transistor. To check a PNP unit, battery connections would be reversed.

the signal voltage applied to the input terminals and then the signal voltage appearing across the output. An audio oscillator will serve nicely as the signal source. The gain of the stage is then computed from the ratio of output voltage to input voltage. This value can be compared with the rated value (for a grounded emitter amplifier) or with that of similar transistors known to be good.

The arrangement shown is for an NPN transistor. For a PNP unit, the battery polarity would be reversed.

The tester is simple to operate and will provide enough of an indication to enable the technician to judge the operating ability of the transistor under test. Where it might sometimes fall down is in the

* Several inexpensive checkers are being advertised as this book goes to press. One of these is being produced by General Electric and uses substantially the circuit shown in Fig. 5.

checking of transistors used in high-frequency circuits, such as the
i-f, r-f, or oscillator stages of a radio receiver. It can happen that such
units will give a "good" indication at low frequencies but a "poor"
indication at higher frequencies. The only way to uncover such transis-
tors would be to check them at their operating frequency. If this is not
feasible, substitution will be required.

Another simple test that may be employed has been suggested by
General Electric. This is based on the fact that a very revealing charac-
teristic of a transistor is the collector current that flows when the emit-
ter is grounded and no signal is applied to the base. This current is a
function of the temperature and the resistivity of the germanium and,
most important, becomes quite large if there is contamination on the
surfaces of the germanium or if the transistor has been damaged by a
short circuit. A simple circuit with which to check this current is shown
in Fig. 3.
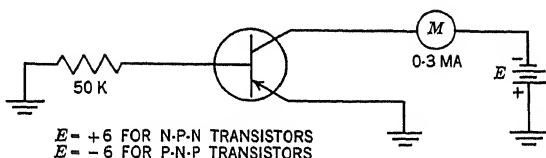
FIG. 3. A simple circuit to check collector current when emitter is grounded and
no signal is applied to the base.

If the collector current of the transistor is greater than 0.75 ma at
room temperature for a 2N135, 2N136, 2N44, 2N45, or 2N78 or greater
than 2 ma for a 2N137 or 2N43, it should be replaced. For other transis-
tor types, the limit of collector current as revealed by this test is ar-
rived at as follows: From the manufacturer's data sheet for that transis-
tor, obtain the maximum value of I_{co} and the maximum value of β. (If
α is given, but not β, then compute β from the relationship existing be-
tween these two constants as given in Chap. 3.) Multiply β and I_{co}
together, and then further multiply their product by a factor of 3. The
answer represents the limit of collector current tolerable according to
the above test. The factor of 3 is a "leeway" factor to take into account
manufacturing variations in β and I_{co} for a transistor. Generally, a "bad"
transistor will greatly exceed the collector current limit established by
the above formula.

Another good test of a transistor is to put a small current into the
base and check the current amplification (change in collector current
caused by a change in base current). This current gain β can be
checked by the circuit shown in Fig. 4. When the switch is closed,

the base current increases 0.03 ma. For a good transistor, the collector current, as indicated by the current meter, should increase by at least 0.3 ma (for $\beta = 10$). With a higher transistor, the current increase may go as high as 3 ma ($\beta = 100$). In any event, check the value of β you obtain with that specified by the manufacturer. If your value is appreciably lower than the normal value, change the transistor.
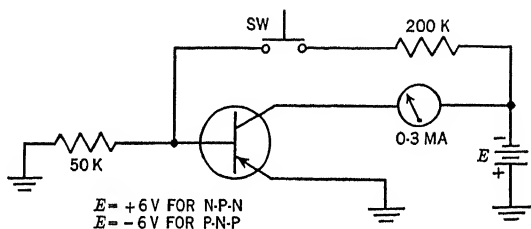
FIG. 4. A simple circuit designed to reveal β of a transistor.

It is possible to combine the two foregoing circuits to make a portable transistor checker good for either NPN or PNP transistors. The circuit is shown in Fig. 5. The procedure for testing a transistor would be as follows:
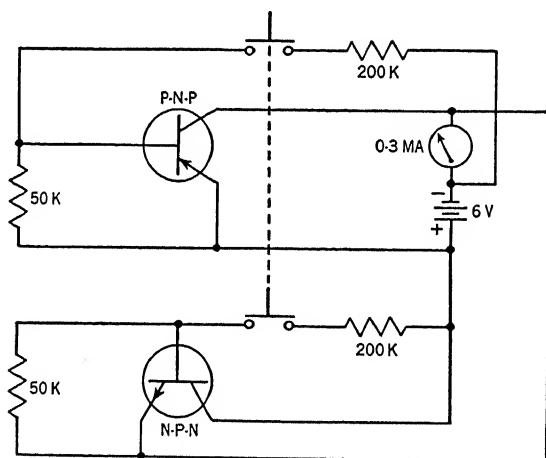
FIG. 5. A combined circuit incorporating the separate circuits of Figs. 3 and 4.

1. Insert the transistor in the proper socket, or attach it to the proper terminals if a socket is not used.

2. Check to make certain that the leakage current is no greater than the limits indicated for that unit.

3. Depress the push button, and check to see that the current increases at least 0.3 ma.

4. Check the battery voltage periodically by inserting a 2,000-ohm resistor in either socket between emitter and collector. With good batteries, the meter should read close to 3 ma.

These tests will determine if a transistor is good or bad, but it will, in no way, reveal its frequency response.

COMPONENT CHECKING OTHER THAN TRANSISTORS

In addition to transistors, there are other components in these miniaturized circuits that may offer the service technician more difficulty than he might ordinarily encounter. This is particularly true of electrolytic capacitors which, because of the low voltages used, have rated working voltages far below those of conventional units. In a transistor radio, a coupling capacitor having a value of 3 μf may be rated at 6 volts or less. If you attempt to check such a unit with a conventional capacitor checker in which the test voltage is generally much higher than 10 volts, you will probably ruin the miniature capacitor.

Again, one solution to this problem is substitution, although this is generally the more difficult approach, particularly in the printed wiring circuits common with transistors. Another solution is by means of a vacuum-tube voltmeter using the ohmmeter scale. (Note again that the strength of the test voltage should be carefully checked to make certain it does not exceed the capacitor rating.) If an electrolytic capacitor is suspected of being faulty, disconnect one lead from the circuit and make a resistance check of the unit. Since these units possess a relatively high capacitance value, it is recommended that they be checked on the $R \times 10,000$ range. When the meter leads are connected across the capacitor (with proper polarity observance), the meter needle will deflect across the scale and then gradually return to its infinite resistance position. The smaller the capacitor value, the more quickly the needle will move back to its original position. An open capacitor will not produce any meter deflection at all. A leaky capacitor will show a resistance value, and the meter needle will not return to full scale when an ohmmeter measurement is taken.

The same method can also be employed to check paper, mica, and ceramic capacitors. Each of these will show a slight deflection on a high-resistance range ($R \times 1$ megohm), and the reading will return quickly to full scale. The smaller the capacitance value of the unit, the smaller the needle swing. Eventually, this test becomes inconclusive when the capacitance becomes too small. (Offsetting this apparent

limitation is the fact that the small mica, paper, and ceramic capacitances generally have voltage ratings high enough to permit checking on a regular capacitor checker.)

Of the other components in a transistor receiver, inductors and resistors generally offer no test problems, since they can be checked in the usual manner by voltmeters or vacuum-tube voltmeters.

PRINTED CIRCUITS

Transistors are used extensively with printed circuits, and so it behooves the technician to become familiar with the proper methods of removing or adding components to a printed wiring chassis. The following discussion will be helpful in this respect.*

A printed circuit begins as a laminated plastic board with a sheet of thin copper foil bonded to one side. To form the necessary wiring, some of the copper foil is removed by a photographic and etching process. Holes are punched in the board through which various component leads are inserted. The leads of the various components are cut and bent over the copper-foil wiring. The wiring side of the board is then dipped in molten solder to make all solder connections at once. The copper-foil wiring also picks up solder, thus increasing its ability to carry current. Finally a coat of silicone resin varnish is applied to the wiring side of the board. This prevents dust or moisture from causing short circuits. The result is a circuit with uniformity of wiring, compactness, and freedom from wiring errors. (The foregoing method of producing printed wiring boards is known as the etched wiring method. It is used today more widely than any other form of printed wiring. This is largely because of the reliability, great flexibility, and low setup cost of the method. There are, however, other methods of manufacture such as embossed wiring, stamped wiring, and pressed powder wiring. Since we are interested primarily in the end result, none of the other methods will be described.)

Circuit tracing of a printed circuit board is usually simpler than that of conventional wiring owing to the uniform layout of the wiring. Also, many boards are translucent, and a 60-watt light bulb placed underneath the side being traced will facilitate location of connections. Test points can frequently be located rather easily in this manner without the necessity of viewing both sides of the board.

Resistance or continuity measurements of coils, resistors, and some capacitors can be made from the component side of the board. In some

* From information furnished by the Admiral Corporation, "Service Manual No. S559."

cases a magnifying glass will assist in locating very small breaks in the wiring. Voltage measurements can be made on either side of the board. However, on the wiring side of the board,* a needle-point probe for circuit checking should be used, since the varnish coating must be ·pierced to make contact.

Be careful when removing components from the board. However, if the copper-foil wiring is damaged, a piece of wire can be used to replace the damaged foil. Small breaks can be "jumped" with molten solder. Larger breaks can be repaired with ordinary hook-up wire. It is seldom necessary to replace an entire board because of foil breakage.

Do not apply excessive pressure to the printed circuit board or components. Although the board is sturdy in construction and mounting, it may crack or break if proper care is not taken when servicing. On extremely rare occasions, access to components on the board may be difficult. In this case the board may be removed from the chassis by removing the mounting screws around the edges and unsoldering a few leads between the board and the chassis. If this is done, a vise with protected jaws should be used to hold the board while servicing and care should be taken not to exert excessive pressure against the board.

In some areas on the printed board, the wiring is very closely spaced. When resoldering a new component, avoid excessive deposits of solder. Excessive solder may cause a short or intermittent trouble to occur later which may be difficult to locate.

When using the soldering iron (35 watts or less), do not overheat the component terminals or the copper foil. Excessive heat (applying soldering iron longer than necessary, using a higher-wattage iron than recommended, or using a soldering gun) may cause the bond between the board and foil to break. This will necessitate the replacement or repair of the foil connection.

REPLACING CAPACITORS, RESISTORS, COUPLATES, AND PEAKING COILS

Defective resistors, couplates, ceramic disk, and wax-encased capacitors can be replaced by either of the following two methods:

1. If the leads extending from the defective component are long enough for a replacement component to be soldered to it, cut the leads where they enter the defective component (see Fig. 6).

2. If there is not enough length in the leads extending from the defective component to use the method described above, cut the defective component in half. Then cut through each half of the com-

* Some printed circuit boards have component parts on both sides.
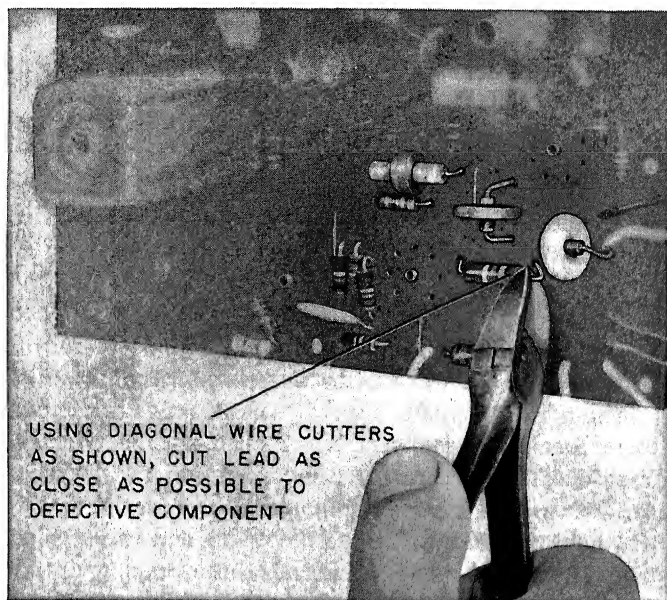
FIG. 6. Cutting a defective resistor free of the printed circuit board. (*Courtesy of Admiral Corp.*)
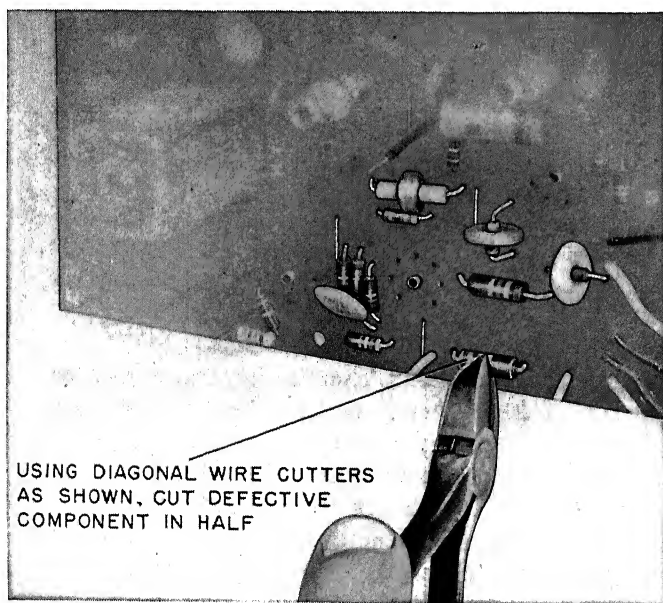
FIG. 7. Cutting a defective resistor apart so as to have maximum lead length left. (*Courtesy Admiral Corp.*)

ponent until it is broken away from its lead. If this procedure is performed carefully, enough extra lead inside the component will be gained to permit soldering the replacement component to it (see Figs. 7 and 8).

USING DIAGONAL WIRE CUTTERS
AS SHOWN, CUT REMAINDER OF
COMPONENT AWAY FROM LEAD
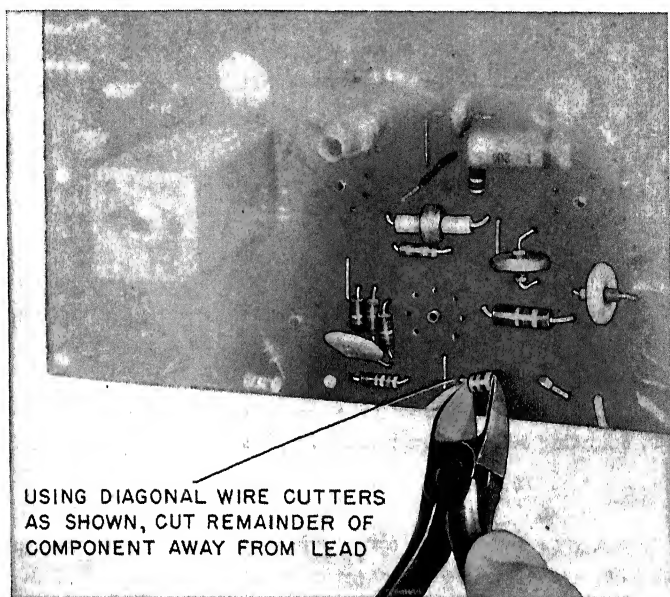
FIG. 8. Cleaning remaining leads of component that has been cut apart. (*Courtesy Admiral Corp.*)

Clean off the ends of the remaining leads, leaving as much of the leads as possible. Make a small loop in each lead of the replacement component, and slide the loops over the remaining leads of the old component (see Fig. 9). Caution should be observed not to overheat the connection, since the copper foil may peel or the original component lead may fall out of the board. This is possible because of heat transfer through the leads. The lead length of the replacement part should be kept reasonably short to provide some mechanical rigidity.

In some cases, components are mounted in such a manner that neither of the above methods can be used. To replace such a component it will be necessary to unsolder the defective component completely and replace it. The following procedure should be used whenever it is necessary to unsolder any connections to replace defective components.

1. Heat the connection on the wiring side of the board with a small

LOOP LEADS OF REPLACEMENT COMPONENT AROUND
REMAINING LEADS OF OLD COMPONENT AND SOLDER
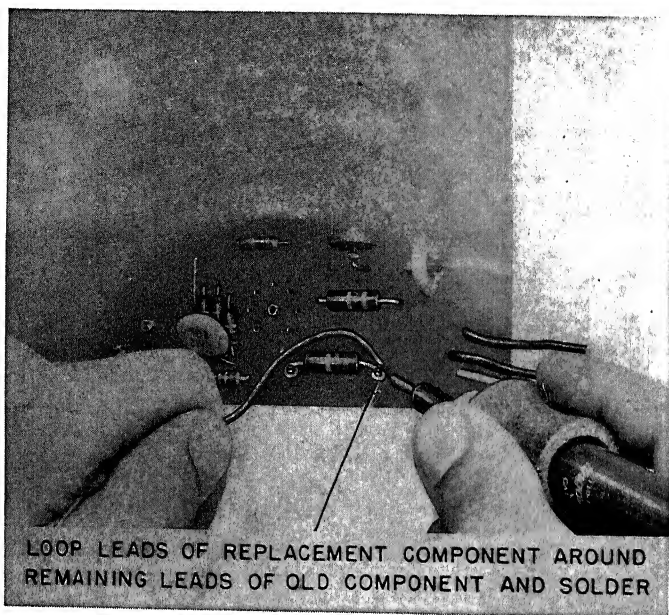
FIG. 9. Soldering replacement resistor in place. (*Courtesy Admiral Corp.*)

COMPONENT LEAD BRUSHED
FREE OF SOLDER AND BENT UP

WIRE BRUSH

REMAINING LEAD ABOUT TO BE CLEANED OF SOLDER
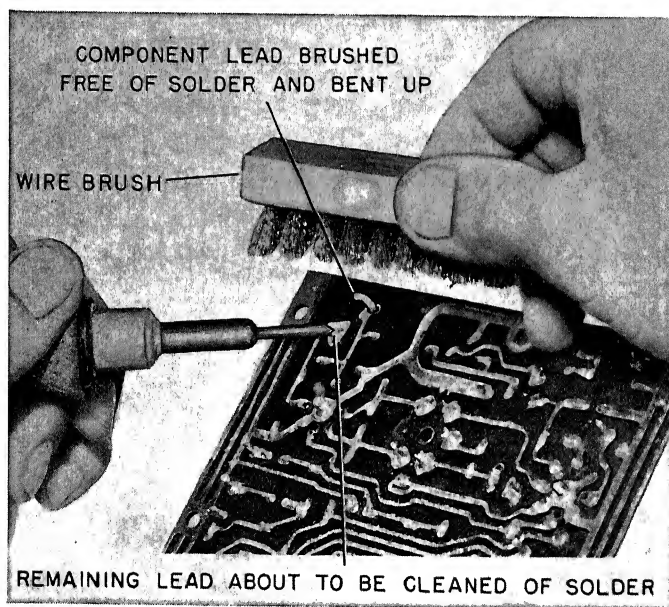
FIG. 10. All excess solder should be carefully brushed away. (*Courtesy Admiral Corp.*)

soldering iron. When the solder becomes molten, brush away the solder (see Fig. 10). A 60-watt bulb placed over the component side of the board will facilitate location of the connections on the wiring side if the board is translucent (and many of them are). In the process of removing the solder, caution is needed to prevent excessive heating. Therefore, do not leave the iron on the connection while brushing away the solder. Melt the molten solder, remove the iron, and quickly brush away the solder. (For this purpose, a small wire brush is suitable.) It may require more than one heating and brushing process to remove the solder completely.

2. Insert a knife blade between the wiring foil and the "bent-over" component lead, and bend the lead perpendicular to the board. (It may be necessary to apply the soldering iron to the connection while performing this step, as it is sometimes difficult to break the connection completely by brushing.) Do not overheat the connection.

3. While applying the soldering iron to the connections, "wiggle" the component until it is removed.

4. Remove any small particles of solder embedded in the silicone resin (if such a coating is employed) using a clean cloth dipped in solvent.

5. A thin film of solder may remain over the hole through the board after removing the component. Pierce the film with the lead from the new component after heating the solder film with the soldering iron.

6. Insert the leads of the new component through the holes provided. Cut to desired length, and bend over the ends against the copper foil. Resolder the connection with 60/40 low-temperature solder.

7. It is recommended that the cleaned area be recoated with clear lacquer or sprayed with Krylon for protection against shorts. If the Krylon spray is used, it will be necessary to cover the top of the tube sockets and chassis ground connections with masking tape to prevent the contact surfaces from becoming coated.

REPLACING COILS

The terminal lugs of these components are not "bent over" against the foil in most cases. Therefore, brushing is not necessary. Heat one connection until the solder becomes molten, and wiggle the coil back and forth until the connection is broken. Continue to wiggle and apply the soldering iron to the other connections, and lift the coil from the board while the solder is still molten. Insert the replacement coil in the exact same position, and solder the connections. Cover the connection points with a coat of lacquer or Krylon.

REPLACING THE RATIO DETECTOR AND
I-F TRANSFORMERS

These units have anywhere from four to seven soldered lugs, and replacing them requires more time and patience than required for other components. The following procedure is recommended in these instances:

1. Apply the soldering iron to one of the connecting lugs (see Fig. 11). Note: On some transformers, it will be necessary to bend the
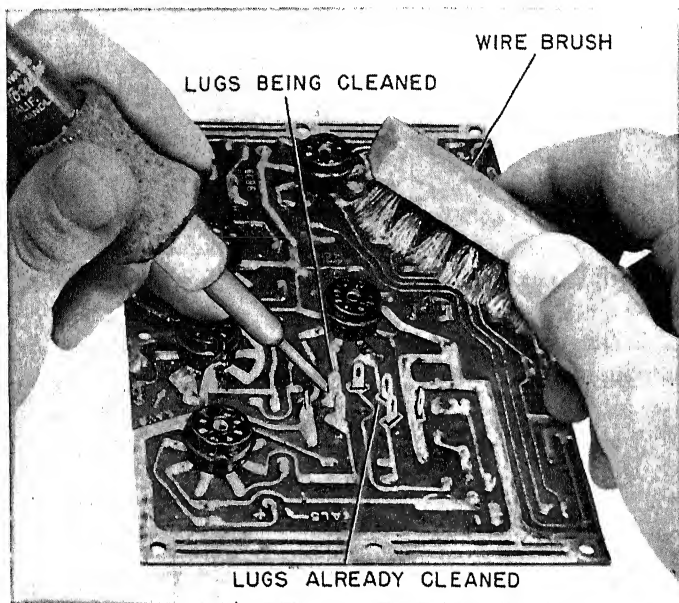
FIG. 11. Removing defective can-mounted transformer. (*Courtesy Admiral Corp.*)

mounting lugs perpendicular to the board while the solder is molten so as to be able to brush away the solder.

2. Cut off the transformer lugs as close to the board as possible. Repeat step 1. Use a cloth dipped in thinner to clean away any specks of solder stuck to the board.

3. Insert the replacement transformer, and solder the connections. Note: No special precautions are necessary when mounting the new transformer. It is not necessary to twist the transformer mounting lugs of the new transformer before soldering.

4. Cover the connection points with a coat of lacquer or Krylon, observing the precautions given previously.

TRANSISTOR RECEIVER SERVICING

Transistor servicing does not differ appreciably from the servicing of vacuum-tube-operated receivers. There are, however, certain differences of initial approach due to the use of batteries and transistors, and it is these differences (rather than the more familiar similarities) which will be considered here.

For example, when the output of a transistor receiver is distorted, weak, or completely dead, the prime suspect is the battery. The measurement is made with a vacuum-tube voltmeter or high-resistance voltmeter and is best taken with the battery in the receiver and the latter turned on. If the voltage reading is at or near the correct value, the battery can be presumed to be good. If the voltage reading is off by 20 per cent or more, then the receiver output may be weak or distorted, but it should not be dead. Since transistor characteristics are linear to very low voltages and currents, chances are that distortion will not occur until the battery voltage drops more than 20 per cent. There is, however, no set rule regarding this, and it is best to try a new battery when the voltage of the existing battery has decreased by this amount. If the distortion or weakness still persists, then some other defect is indicated.

Whenever a weak battery is found, it may be advisable to check the resistance of the circuit across the battery clips before a new unit is inserted. For example, in the Regency model TR-1 receiver, the manufacturer indicates that the resistance between the battery clips (with the battery removed and the receiver turned on) should be between 6,000 and 15,000 ohms as read by an ohmmeter with an internal battery of not more than 3 volts. A reading lower than 6,000 ohms will usually indicate a defective component somewhere in the receiver.

Some manufacturers indicate what the current drain on the battery should be instead of quoting the circuit resistance across the battery clips. In this case, a milliameter must be inserted in series with the battery. For example, with the negative terminal of the battery touching the negative clip, a wire is connected from the negative terminal of the milliameter to the positive battery clip. Then one end of another wire is connected to the positive terminal of the milliameter while the other end of this wire is touched to the positive end of the battery. The value of current indicated on the meter should fall in the range specified by the manufacturer.

If the battery proves to be good, then the rest of the trouble-shooting procedure follows established practice. As an example of this, the method of attack for the Regency model TR-1, as recommended by

the manufacturer, is given below. Study this in conjunction with the schematic diagram of the set. The latter will be found in Fig. 3, Chap. 6.

The alignment procedure for the same receiver is given also following the trouble-shooting outline.

TROUBLE-SHOOTING PROCEDURE FOR THE REGENCY MODEL TR-1 RECEIVER *

Dead Receiver—Absolutely No Output

1. Remove the battery and turn on the switch. Measure the resistance between the battery clips. (Make sure the positive meter lead is on the positive clip.) If the resistance is

    a. Approximately 10,000 ohms, the B+ circuit is normal.

    b. Less than 2,500 ohms, check the leads of capacitors C_{17} and C_{21}, and make sure they are not touching the battery clips or the frame of the output transformer. Check for a shorted condition in either C_{17} or C_{21}. Measure the resistances from the top ends of R_3 and R_7 to ground. These should be 2,200 ohms more than the reading across the battery clips.

    c. Infinity, check for an open switch.

2. Turn the volume control to maximum, and insert the battery. If a click or noise is heard from the speaker, check V_5 by shorting its base to the frame of the output transformer. The audio stage is operating if a click is heard. If no click or noise is heard, proceed as follows:

    a. Check for an open or shorted jack. Indicative readings can be obtained by measuring the resistance from the fixed contact of the jack to ground. These readings are

      0 ohms—shorted jack

      2 ohms—normal

      15 ohms—jack is open, or the ground between the wiring board and chassis is open

    b. Check for an open condition in the speaker or in the output transformer.

    c. Voltage at the base of V_5 (about +2 volts normal).

    d. Voltage at the emitter of V_5 (should measure approximately 0.15 volt less than the base voltage).

3. Check capacitor C_{19} by paralleling it with a capacitor known to be good.

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* Reprinted from *PF Reporter*, March, 1955, with permission of Howard W. Sams & Co., Inc.

4. Measure the voltage at the output of the diode V_4 (should be approximately +0.1 volt).

    a. If voltage is zero, check the resistance to ground with the positive meter lead on the output. This resistance should measure between 20 and 100 ohms. If the resistance is zero, check for a shorted condition in the diode circuit. If the resistance is 200 ohms or greater, check for an open in the diode circuit or for an open diode.

    b. If voltage is negative when the receiver is tuned to a station, move the tuning dial so that no station is received. The negative voltage should decrease.

    c. If voltage is negative by 1 volt or more and does not drop when the receiver is tuned off the station, the receiver is oscillating. Proceed to the section entitled Oscillating Receiver.

5. Make voltage and resistance measurements in the i-f stages.

Dead Receiver—Noise but No Signal

Check the local oscillator in the receiver as follows: Tune another receiver to any station above 850 kc. On the receiver being serviced, rock the dial above and below a setting that is approximately 262 kc below the frequency of the station being received by the other receiver. If the local oscillator in the receiver being serviced is operating, a whistle will be heard from the other receiver as the radiation from the oscillator beats with the station frequency.

If the oscillator is dead, proceed as follows:

1. Check the voltage at the base of V_1. This should be between 3 and 10 volts.

2. Check the voltage at the emitter of V_1. This voltage should be within 0.1 volt of the base voltage.

3. Check the voltage at the top end of R_3. This should be measured from the B+ line, and it should be between 0.6 and 2 volts.

4. If any of the voltages measured in the three preceding steps are incorrect, check for an open oscillator-coil primary or an open first i-f transformer.

5. Check resistances of

    a. The high side of the antenna coupling coil to ground (should be less than 1 ohm).

    b. The secondary of the oscillator coil (should be approximately 10 ohms).

    c. Stator of oscillator section of the tuning capacitor to ground (should be infinity).

Weak or Distorted Output

1. Turn volume control to maximum. Check capacitors C_{19} and C_{21} by paralleling a good capacitor across each.

2. Perform step 5 under section Dead Receiver—Absolutely No Output.

3. Measure voltages at
   a. Base of V_5 (should be approximately $+2$ volts).
   b. Emitter of V_5 (should be approximately 0.15 volt less than the base voltage).
   c. Emitter of V_3 (should be approximately 0.15 volt less than the voltage at the emitter of V_4).
   d. Top end of R_{11} (should be approximately -0.5 volt when receiving a signal of average strength).
   e. A-v-c line (should be from approximately 0 volt with signal to 0.5 volt with no signal).
   f. Emitter of V_2 (should be approximately 0.15 volt less than the a-v-c line).

4. Check the alignment of the receiver.

Oscillating Receiver

1. Measure the battery voltage. If it is below 15 volts, the battery should be replaced.

2. Check the local oscillator as in step 1 under the section entitled Noise but No Signal.

3. Check capacitors C_{17}, C_9, and C_{21} by paralleling a good capacitor across each.

4. Check ground connection between wiring board and chassis. This connection is the twisted lug near the negative battery clip and is the only lug which has been soldered to the board. Measure between an i-f transformer can and the metal chassis. These readings are

   0 ohms—normal

   15 ohms—ground lead is open

ALIGNMENT OF REGENCY MODEL TR-1 RECEIVER

The alignment of the Regency receiver is quite simple. Signal injection is accomplished by connecting the signal generator to a loop formed of several turns of wire and situated close to the antenna coil of the receiver. Set the generator to 262 kc with 400-cycle modulation, and reduce the output to as low a value as is usable. Connect an output

meter (with a 0.1-volt scale) across the voice-coil terminals. (The high side of the voice coil is easily accessible at the spring of the phone jack in this set.) Set the volume control in the receiver to maximum. Adjust each of the cores of the i-f transformers for maximum indication on the output meter. Set the receiver dial to its maximum counterclockwise position, tune the generator to 535 kc, and adjust the core of the oscillator coil for maximum output. Tune the generator to 1,630 kc, set the receiver dial to its maximum clockwise position, and adjust the oscillator trimmer capacitor for maximum output. Repeat these last two adjustments alternately until no further improvements can be made. Then tune the generator to 1,500 kc, tune in this signal with the receiver dial, and adjust the antenna trimmer capacitor for maximum output. Turn the receiver dial to the high-frequency end, and determine whether or not the range extends to 1,630 kc. If not, the oscillator trimmer capacitor must be readjusted and the alignment at 1,500 kc must be repeated.

QUESTIONS

1. In what respects are transistors sturdy? In what respects fragile?

2. What changes in working tools are necessary when dealing with transistors and their associated components?

3. Indicate several precautions to follow when soldering transistors into a circuit.

4. Why are transistors especially sensitive to applied voltages?

5. Outline the precautions to observe when injecting signals into a transistor circuit. Indicate a suitable safe method of bringing such signals into a circuit.

6. How could one determine whether a transistor was good or bad?

7. Outline a procedure for checking capacitors using a vacuum-tube voltmeter.

8. What limitations does the foregoing method of capacitor checking possess?

9. Indicate generally the precautions to observe when removing components from printed circuit boards.

10. In what respects does the servicing of transistor receivers differ from the servicing of comparable vacuum-tube sets?

11. Is it better to check a battery (using a vacuum-tube voltmeter) while it is in the circuit or after it has been removed completely from the set? Give reasons for your answer.

12. How would you align the Regency model TR-1 receiver?

13. If it were determined that the oscillator in the Regency receiver was not functioning, how would you proceed to localize the defect?

14. What might cause a weak or distorted output from this receiver?

15. Under what conditions would the battery in the Regency set not be the first component checked? (Assume that the receiver is not functioning properly.)

CHAPTER 10

EXPERIMENTS WITH TRANSISTORS

In the preceding chapters, the theory and application of transistors were covered in detail. The information contained there represents the first step toward the acquisition of a basic understanding of transistor operation. The next step for the man who is going to work with these units is actual physical contact so that he may become practically proficient in handling transistors and learning, first hand, of their characteristics and peculiarities. Toward this end, a series of experiments are presented, and all readers are urged to perform them prior to any work on transistors in commercial equipment.

The circuitry involved in these experiments has been kept as simple as possible. This serves the twofold purpose of making each experiment easy to perform and keeping component cost down. Furthermore, the same basic components are used over and over again. Because of this, caution should be exercised when leads are trimmed prior to soldering lest the amount of wire removed be so much that the unit will not be usable for as many times as required.

Another very important precaution to observe, one that was mentioned in the chapter on transistor servicing, is the use of a low-wattage soldering iron when soldering transistor leads into the circuit. Keep these leads as long as possible, and grip the lead being soldered with a pair of long-nose pliers. Since the lead is held between the point where the heat is applied and the body of the transistor, any heat traveling along the lead wire will be shunted away from the transistor.

It is also important to observe battery polarity when connection is made to the circuit. If the collector terminal receives a forward-biasing voltage in place of a reverse-biasing voltage, the transistor can be damaged permanently. Double-check wiring before connecting any batteries. Do not use voltages higher than those indicated in the experiments. Also make certain that the battery is disconnected before any wiring connections are altered. Finally, be especially careful to avoid

circuit shorts between various wires. If necessary, cover all bare wires (or exposed ends of wires) with protective spaghetti.

No specific chassis form or size is recommended for the ensuing experiments. They may be performed on a bread-board or on any of the small metallic chassis that are obtainable at a parts jobber. In the latter instance, there are a number of standard base sizes ranging generally from 2 by 6 by 4 in. (height, width, depth) to 5 by 17 by 13 in. A recommended size of 3 by 7 by 5 in. was found to be entirely adequate for the experiments; however, any suitable dimensions may be used.

It would also be desirable to use terminal strips on which the components may be mounted. Choice of such strips is left to the reader.

EXPERIMENT 1 *

Adjusting Transistor Voltages and Currents

Object: To adjust the voltages on a transistor and to establish the principle of phase reversal in a grounded-emitter amplifier.

Material Required:

1 2-μf electrolytic capacitor
1 0.01-μf capacitor
1 1-megohm potentiometer
1 CK722 transistor (or equivalent)†
3 10,000-ohm resistors (¼ watt)
1 3-volt battery

Test Equipment:

1 vacuum-tube voltmeter or a good multimeter (preferably 20,000 ohms per volt)

Procedure:

1. Wire the circuit of Fig. 1.
2. Check all connections before attaching the battery.

* A kit containing all the necessary components to perform the following experiments is commercially available. For information concerning cost and name of manufacturer, write to the author, c/o McGraw-Hill Book Company, Inc., 330 West 42nd Street, New York 36, N.Y.

† Any low-frequency PNP transistor which operates with the voltages noted would be suitable in place of the recommended CK722. Other high-frequency and/or higher-power transistors could also be employed, but these units generally cost more, and they would not provide any more useful information (in these experiments) than the inexpensive transistors.

3. Connect the battery, and adjust P_1 until the voltage between base and ground is −0.1 volt. The collector will then be between −0.5 and −1 volt with respect to ground.

4. Leave the voltmeter connected to the collector. Take a 10,000-ohm resistor, and touch it between base lead and ground. Notice how
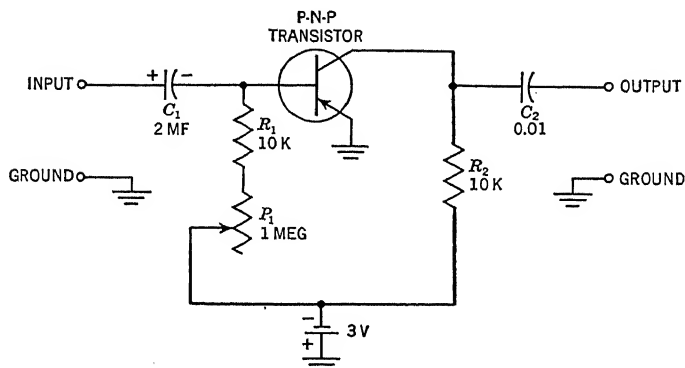
Fig. 1

the collector potential becomes more negative. When the 10,000-ohm resistor was touched from the base to ground, it caused the base to become less negative, or more positive. At the same time the collector became more negative.

Conclusions:

1. The principal conclusion that can be drawn from the foregoing behavior is that a grounded-emitter amplifier reverses the phase of an applied signal.

2. As a secondary consideration, it was noted that as P_1 was rotated, it varied the base and collector voltages. We could also conclude that if a resistor had been inserted in the emitter lead, the voltage drop across this resistor would have varied also. Ninety-five per cent of the emitter current passes through the collector, and if we vary the collector current, we must also vary the emitter current.

EXPERIMENT 2

Distortion and Temperature Effects

Object: To observe the operation of a single-stage transistor with signal input and to demonstrate the effect of temperature change.

Material Required:

1 2-μf electrolytic capacitor
2 0.01-μf capacitors
1 1-megohm potentiometer
2 CK722 transistors (or equivalent)
2 10,000-ohm resistors (¼ watt)
1 3-volt battery

Test Equipment:

1 audio signal generator or a filament transformer arrangement as shown in Fig. 2
1 oscilloscope

FILAMENT
TRANSFORMER

TO
POWER
LINE

110V
60~   6.3 V

100 K

10 K   60~ OUTPUT
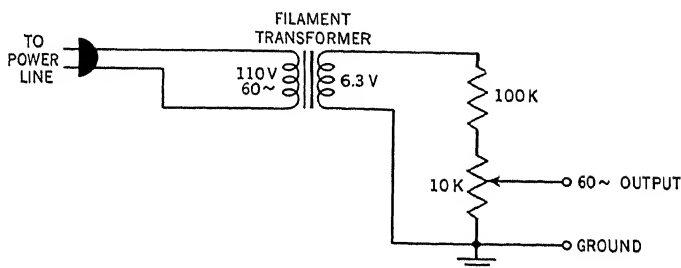
GROUND

FIG. 2

Procedure:

1. Apply a very low-voltage signal, about 0.01 volt rms, between C_1 and ground in Fig. 1. An audio oscillator is desirable for this purpose. (Be careful not to use too strong a signal because the transistor can be ruptured by overdrive.) The signal lead goes to C_1, while the other generator lead goes to ground. If an audio oscillator is not available, a filament transformer can be used with the circuit shown in Fig. 2.

2. Connect the vertical input terminals of an oscilloscope between the output of C_2 (Fig. 1) and ground.

3. Starting from zero, adjust the output of the audio generator until an undistorted sine-wave signal is just seen on the oscilloscope.

4. By varying P_1, the least distorted signal may be obtained. Note, when adjusting P_1, how the output signal reaches a peak and then starts clipping. The clipping occurs on the negative half cycle of the input signal. While this portion of the signal is active, the collector voltage is actually becoming less negative because the collector cur-

rent is increasing. At the negative input peak, the voltage drop across load resistor R_2 is almost equal to the battery voltage. Further increase in input signal cannot further lower the collector voltage, and the output signal flattens out or clips. This is similar to plate clipping in a vacuum tube.

If the input signal is increased beyond this point, clipping of the other half cycle also results. This occurs when the positive half cycle of the applied signal causes the emitter-to-base voltage to reach the reverse bias or cutoff region. Collector current is cut off too, at the same time.

5. Signal leakage may be observed by adjusting P_1 until an undistorted signal is observed and then disconnecting the battery. Notice how the input signal goes through the transistor and appears at the collector. It possesses the reverse phase from that normally seen on the collector, it is usually distorted, and, of course, there is no gain.

6. Reconnect the battery. With a vacuum-tube voltmeter or an oscilloscope, measure the input and output signals. The ratio of the output to input signals is the signal gain. After a numerical value is obtained, convert it to an equivalent decibel figure.

7. Readjust P_1 for the best possible gain with a fixed input signal. Without changing any of the instrument settings, note the height and waveform of the output signal. Hold your fingers on the shell of the transistor, thereby warming it. Do not hold the unit for more than a minute or so. Note how the output signal changes as the transistor cools down.

The above effect is best demonstrated when your fingers are warm. If necessary, rub your hands together slightly to warm the fingers. Do not apply any other heat. The amplitude of the input signal should be such that the output signal is just below distortion on top and bottom.

8. With the signal returned to normal and P_1 adjusted for maximum undistorted output, disconnect the battery and change transistors. Do not touch any of the other settings. Reconnect the battery, and notice how the amplitude of the signal has changed. It may be even quite distorted. Readjust P_1 for the least distorted signal.

Conclusions:

1. Clipping occurs when the signal is too strong.

2. Transistors are very sensitive to temperature variations.

3. The base voltage may frequently have to be adjusted for each transistor.

4. The characteristics of transistors of the same type will often vary

considerably. (In time it is expected that the variations among individual units will become less and less.)

5. A very definite voltage gain is obtained with grounded-emitter amplifiers.

EXPERIMENT 3

Compensation, Input Impedance, and Bias

Object: To establish temperature compensation, to note the effects of emitter degeneration on input impedance, and to note the effects of collector voltage on gain.

Material Required:

2 CK722 transistors (or equivalent)
2 2-μf electrolytic capacitors
1 0.01-μf capacitor
1 2,700-ohm resistor (¼ watt)
2 10,000-ohm resistors (¼ watt)
1 22,000-ohm resistor (¼ watt)
1 1,000-ohm resistor (¼ watt)
1 3-volt battery
1 4.5-volt battery

Test Equipment:

1 audio signal generator or filament transformer arrangement as mentioned in Experiment 2
1 oscilloscope

Procedure:

1. Note the gain, or output signal level, in Experiment 2.
2. Change the circuit to that shown in Fig. 3.
3. Note how the gain has fallen. This may be explained as follows: Voltage measurements will show that the base and emitter voltages are higher than before but the base-to-emitter voltage is still about −0.1 volt. The collector voltage, on the other hand, is still the same. Consequently, the collector-to-base voltage is lower, and this accounts for the lower gain.
4. Try changing transistors. Note that transistors may now be changed without further adjustment. The circuit is much more stable because any variation in I_{co} (collector saturation current) is being

minimized by the degeneration introduced by R_4. This is also true for temperature changes.

5. Increase the battery voltage to -4.5 volts. Notice how the gain increases. This is because of the higher collector-to-base voltage. The transistor can also handle greater power with this increase. Do not go any higher than -4.5 volts.
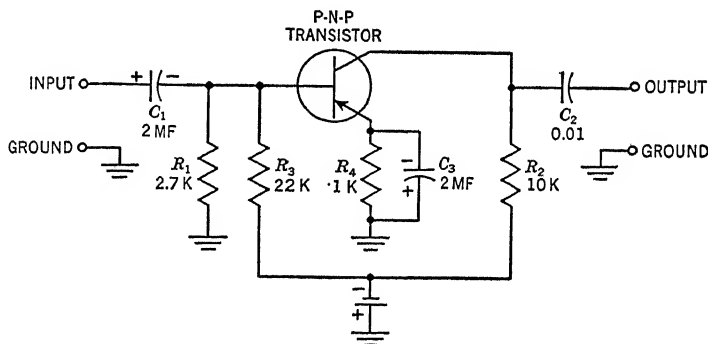
FIG. 3

6. Measure the gain of the stage by dividing the output signal voltage by the input signal voltage.

7. Note the amplitude of the output voltage and then remove the emitter bypass capacitor C_3. Notice how the gain drops markedly.

8. The input impedance will also increase if the bypass capacitor is removed. This can be shown as follows:

a. Reconnect the bypass capacitor C_3.

b. Place a 10,000-ohm resistor in series with the signal input generator and the input capacitor C_1 (Fig. 4).
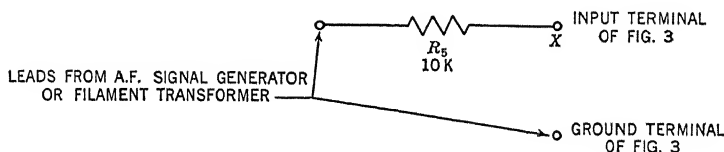
FIG. 4

c. Adjust the output of the signal generator for maximum undistorted output from C_2.

d. Note the height of the input signal at the junction of C_1 and R_5 (point X in Fig. 4).

Remove C_3, and note the increase in input signal at point X. This

action can be explained as follows: With the bypass capacitor in the circuit, the base loading caused a voltage drop across R_5. When the bypass capacitor was removed, the loading was reduced and consequently more of the input signal became available to the transistor. Changes in input impedance of 5 or even 10 to 1 are common.

Conclusions:

1. Emitter compensation improves the temperature stability of the transistor.

2. Emitter compensation permits different transistors to be employed without separately adjusting the circuit for each.

3. The emitter bypass capacitor eliminates signal degeneration.

4. Removing the bypass capacitor increases the input impedance.

5. The higher the collector-to-base voltage, the greater the gain.

EXPERIMENT 4

Grounded-base, Grounded-emitter, and Grounded-collector Amplifiers

Object: To determine the relative differences among the grounded-emitter, the grounded-base, and the grounded-collector amplifier.

Material Required:

1 CK722 transistor (or equivalent)
1 0.01-μf capacitor
2 2-μf electrolytic capacitors
1 2,700-ohm resistor ($\frac{1}{4}$ watt)
1 22,000-ohm resistor ($\frac{1}{4}$ watt)
2 10,000-ohm resistors ($\frac{1}{4}$ watt)
1 1,000-ohm resistor ($\frac{1}{4}$ watt)
1 4.5-volt battery

Test Equipment:

1 oscilloscope
1 audio signal generator or filament transformer arrangement

Procedure:

1. Wire the circuit of Fig. 5.

2. Connect the vertical input terminals of an oscilloscope between the output (at C_2) and ground.

3. Feed an input signal (through a 2-μf electrolytic capacitor and a 10,000-ohm resistor in series, Fig. 6) to the input (which is the base lead).

4. Increase the signal input until maximum undistorted output is obtained. Check the magnitude of the output signal, and also check the gain. The latter measurement should be taken as output voltage divided by the input voltage at point A (Fig. 6) and then computed
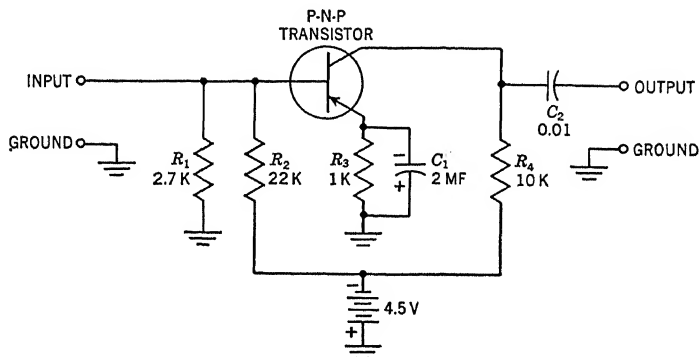
Fig. 5

again as output voltage divided by the generator voltage at point B.

There will be a difference between these two values due to the voltage drop across the 10,000-ohm resistor through which the signal is fed to the amplifier. This drop is caused by the input impedance of the transistor amplifier.

The true gain figure is that value obtained when the output voltage is divided by the input voltage at point A.
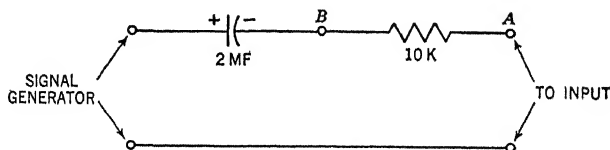
Fig. 6

5. Connect a 0.01-μf capacitor from the collector of the transistor amplifier to the *external sync* terminal of an oscilloscope. When the instrument is properly synchronized, check the phase of the signal at the output and input terminals of the amplifier. The two waveforms should be 180° out of phase.

6. Repeat steps 1 through 5 using the circuit of Fig. 7, which is a grounded-base amplifier. Although the base does not go to ground directly, the bypass capacitor essentially brings it to ground so far as alternating current is concerned.

7. Repeat steps 1 through 5 using the circuit of Fig. 8. This is a grounded-collector amplifier. The 2-μf capacitor from collector to ground places this element at a-c ground potential.
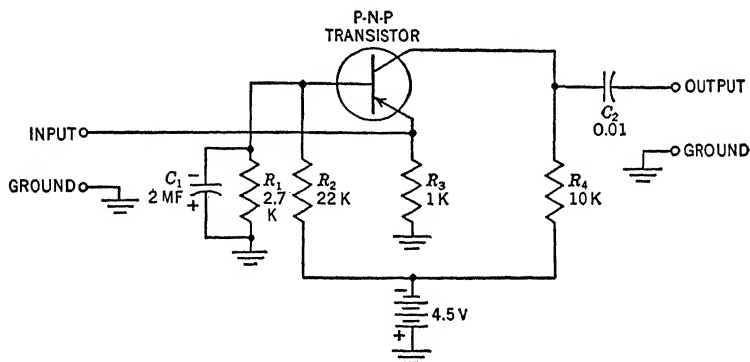
FIG. 7

Conclusions:

1. The input and output signals of a grounded-emitter stage are 180° out of phase.

2. The input and output signals of a grounded-base stage are in phase. The same is true of a ground-collector amplifier.

3. The grounded-base amplifier possesses a somewhat lower gain
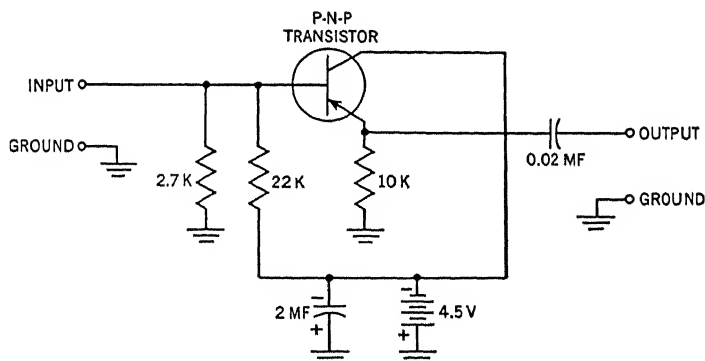
FIG. 8

than the grounded-emitter amplifier. Furthermore, the input impedance of a grounded-base amplifier is lower than it is in a grounded-emitter stage. This was shown by the greater signal drop across the series 10,000-ohm resistor. The grounded-collector stage possesses a gain

less than 1. However, its input impedance is the highest of all three arrangements.

Actually to measure the input impedance of any of these amplifiers, substitute a 100,000-ohm potentiometer for the 10,000-ohm resistor of Fig. 6. As an initial step, adjust this potentiometer for zero resistance (i.e., short it out of the circuit). Now feed in just enough signal for maximum undistorted output on the oscilloscope connected across the output terminals.

Note the amplitude of the signal on the scope screen. (The easiest way of doing this is by having the pattern cover a specific number of squares on a calibrated screen overlay mask.) Then gradually increase the resistance of the potentiometer until the amplitude of the output signal has been reduced to half. The resistance of the potentiometer at this point equals the input impedance of the amplifier circuit.

EXPERIMENT 5

Resistance-capacitance and Impedance Coupling

Object: To observe a two-stage audio amplifier with *RC* and impedance coupling.

Material Required:

1 0.01-μf capacitor
4 2-μf electrolytic capacitors
1 2,200-ohm resistor (¼ watt)
2 22,000-ohm resistors (¼ watt)
2 10,000-ohm resistors (¼ watt)
2 2,700-ohm resistors (¼ watt)
1 1,000-ohm resistor (¼ watt)
2 CK722 transistors (or equivalent)
1 interstage transformer*
1 4.5-volt battery

Test Equipment:

1 audio signal generator or filament transformer arrangement as described in Experiment 2
1 oscilloscope
1 vacuum-tube voltmeter

* Miniature interstage audio transformers designed especially for transistors are available at local parts jobbers. A suitable unit would possess a primary impedance of 10,000 ohms and a secondary impedance of 1,000 ohms.

Procedure:

1. Wire the circuit of Fig. 9. This is a two-stage *RC*-coupled transistor audio amplifier.

2. Feed a very low level signal into C_1. The output is taken from C_4 and applied to the vertical input of an oscilloscope. Compute the over-
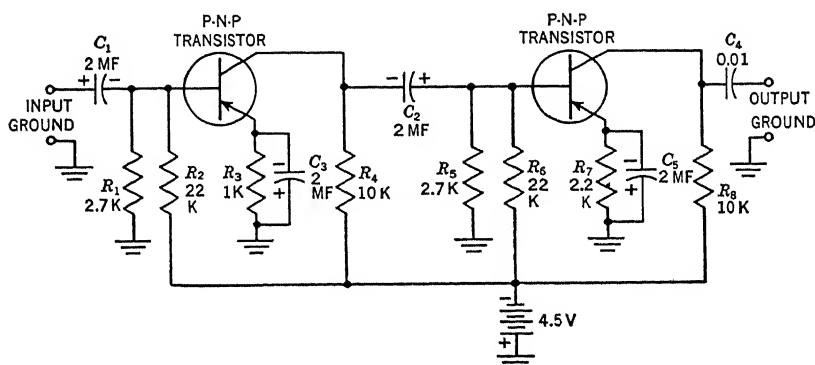
Fɪɢ. 9

all gain of this system. Also compute the individual gain of each stage. This is done by measuring the amplitude of the signal at the base and collector of each transistor and then taking the ratio of collector signal to base signal.

4. Increasing the signal input will show clipping of the positive and negative cycles. Do not increase too much, since it is possible to rupture the transistor with too strong a signal input.

4. If a microphone is available, feed its output into the amplifier instead of a signal generator. A considerably amplified version will be seen at the output.

5. Feed the signal generator into the input, and note the maximum undistorted output. Normally this is about 1 volt rms, but it will vary with the type of transistor used.

6. Change to the circuit of Fig. 10 by removing R_4 and substituting the interstage transformer primary. This is impedance coupling. The blue lead goes to B—; the red lead to the collector. Do not connect the secondary. Notice how the signal clips about the same level. The gain is also the same.

7. Remove the transformer, put back R_4, and remove R_8. Connect the primary of the transformer in place of R_8. The blue lead of the transformer connects to B— and the red lead to the collector (see

Fig. 11). Lower the input signal until maximum undistorted output is obtained. The gain will be found to have increased by 5 to 10 times with this arrangement.

What we have just seen may be summarized as follows: In Fig. 9, we had conventional resistance coupling. In Fig. 10, although the col-
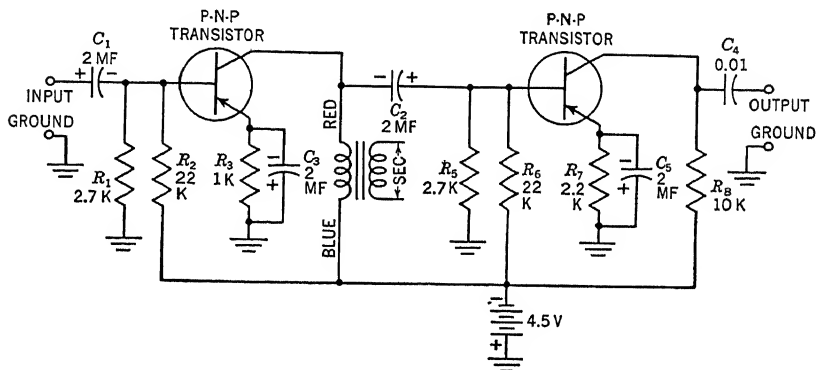
FIG. 10

lector voltage of the first stage was increased, the output could not handle a larger signal than the resistance coupling of Fig. 9. In Fig. 11, however, the output voltage was much greater, since the collector voltage of the second stage was higher. It could, therefore, handle a larger signal from the first stage and also develop a greater output voltage. This indicates that higher outputs require higher collector voltages—a simple achievement with impedance coupling, since there is very little voltage drop through the low d-c resistance of the transformer primary. The a-c resistance, however, is quite high.
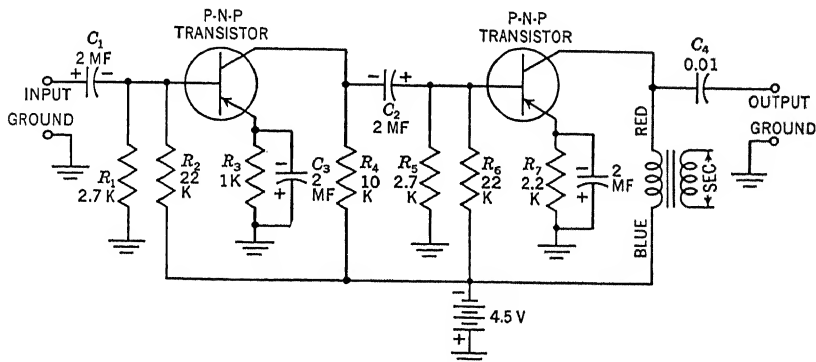
FIG. 11

Conclusions:

1. An *RC* amplifier has considerable gain.

2. Impedance coupling increases the collector voltage and therefore increases the gain and voltage-handling capacity of the stage. It is most valuable in the final stage where it is not hampered by any succeeding amplifiers.

EXPERIMENT 6

Audio-frequency Amplifier with Transformer Coupling

Object: To observe the performance of a transformer-coupled amplifier.

Material Required:

2 CK722 transistors (or equivalent)
4 2-μf electrolytic capacitors
1 0.01-μf capacitor
1 2,200-ohm resistor (¼ watt)
2 22,000-ohm resistors (¼ watt)
2 10,000-ohm resistors (¼ watt)
2 2,700-ohm resistors (¼ watt)
1 1,000-ohm resistor (¼ watt)
1 interstage transformer
1 4.5-volt battery

Test Equipment:

1 audio signal generator or filament transformer arrangement as described in Experiment 2
1 oscilloscope
1 vacuum-tube voltmeter

Procedure:

1. Wire the circuit of Fig. 9 again.
2. Compute the over-all gain.
3. Change to the circuit of Fig. 12.
4. Note the considerable increase in gain. Compute its actual value.
5. An excellent example of the current-amplifying ability of the transistor can be observed by disconnecting C_2 from the transformer secondary and connecting it to the collector of the first transistor. The circuit is now the same as that in Fig. 10. Note how the gain decreases using impedance coupling compared with transformer coupling. This

is in spite of the fact that the signal voltage across the secondary winding is very much lower than it is across the primary winding. The gain, however, increases when the input of the second stage is obtained from the secondary rather than from the larger primary. This is opposite to the action of interstage transformers in vacuum-tube amplifiers. The vacuum tube, of course, operates primarily on a voltage drive, while the transistor operates on a current drive. And the secondary of the transformer possesses a greater current than the primary.
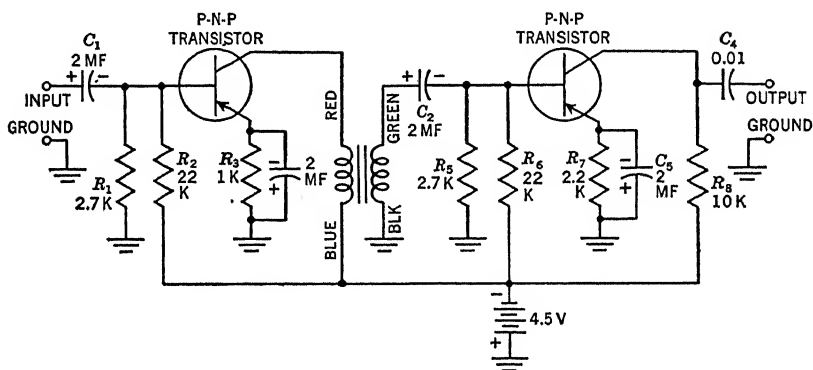
Fig. 12

Conclusions:

1. Transformer coupling increases gain considerably by impedance matching.

2. The transistor is a current-amplifying device.

3. The transistor, in the grounded-emitter connection, has a much higher output impedance than input impedance. This can be more firmly established by rewiring the transformer in the circuit so that the secondary now goes to the collector and B— of the previous stage while the primary connects to the base and ground of the following stage. Note the effect on distortion and over-all gain.

If the reader possesses an audio generator, he might try checking the frequency responses of the *RC*-coupled, impedance-coupled, and transformer-coupled amplifiers. Look particularly for the point where the low-frequency response begins to fall off, where the high-frequency response begins to drop, and also note if the curve is flat between these two end frequencies. If desired, the reader might plot these responses on semilog paper.

EXPERIMENT 7

Complete A-f Amplifier and Supplementary Experiments

Object: To analyze audio amplifiers further.

Material Required:

2 CK722 transistors (or equivalent)
4 2-μf electrolytic capacitors
1 interstage transformer
1 2,200-ohm resistor ($\frac{1}{4}$ watt)
1 1,000-ohm resistor ($\frac{1}{4}$ watt)
3 2,700-ohm resistors ($\frac{1}{4}$ watt)
2 22,000-ohm resistors ($\frac{1}{4}$ watt)
1 1-megohm potentiometer
1 speaker and output transformer
1 phonograph input
1 4.5-volt battery
1 15-volt battery

Test Equipment: None

Procedure:

1. Wire the circuit of Fig. 13. This is the same as Fig. 12 except that a loudspeaker and its output transformer have been added. High-
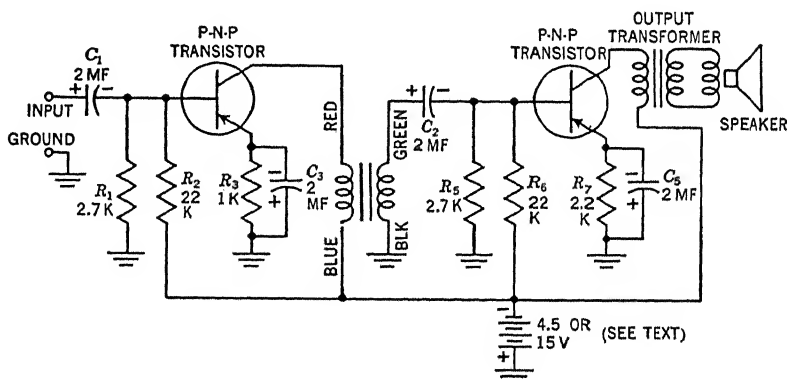
Fig. 13

impedance magnetic earphones (phones with low d-c resistance) may be used in place of the loudspeaker and output transformer.

2. A phonograph pickup is fed into the input. If possible, use a pickup with a high output voltage (i.e., a crystal pickup).

3. By changing to a 15-volt battery, a much greater output can be obtained.

4. Further output power may be developed by decreasing the values of emitter resistors (R_3 and R_7) to 470 ohms each. Additional power output can be obtained by removing all base resistors and connecting
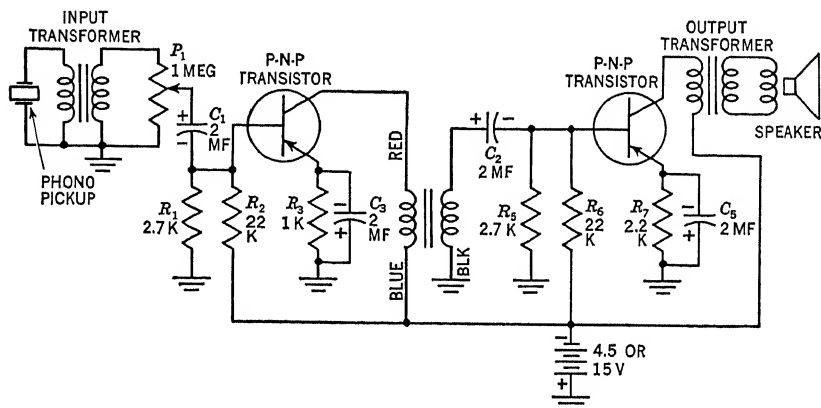
FIG. 14

a potentiometer (1 megohm) from the base of each transistor to B—. The base-to-emitter voltage can be adjusted then for maximum output. Be very careful not to develop more than 0.1 or 0.2 volt negative on the base with respect to the emitter (not ground, since the emitter is not directly connected to ground).
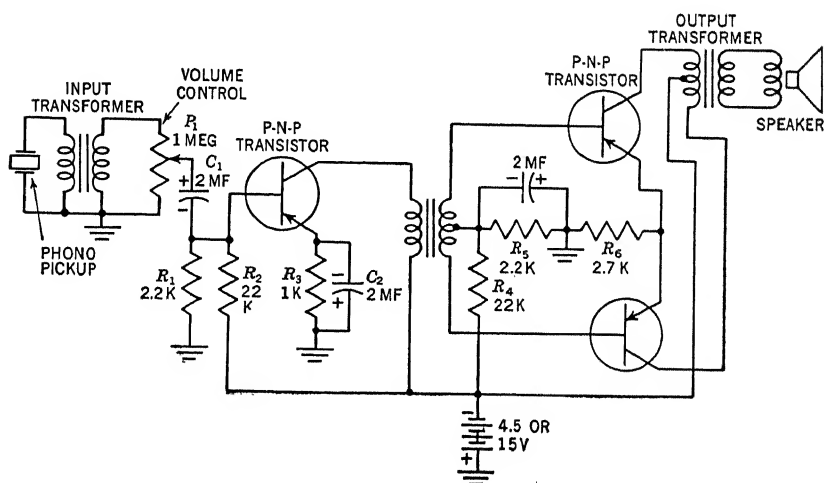
FIG. 15

5. It is startling to measure the total current used with 15 volts as a supply. The drain is about 4 ma, and enough volume is produced to serve an average living room. If more gain is desired, a phonograph step-down transformer may be used to match the relatively high phonograph impedance to the low input impedance of the transistor. The circuit is shown in Fig. 14.

6. An alternate circuit (Fig. 15) contains a push-pull output arrangement. The second-stage emitter bypass capacitor is omitted because the emitter currents are 180° out of phase, eliminating the need for a capacitor. This circuit has the conventional advantage of push-pull operation. A 1-megohm potentiometer has been added as a volume control.

EXPERIMENT 8

Transistor Signal Tracer and Elementary Radio Receiver

Object: To construct a signal tracer and then tune it, thereby converting it to a tuned signal tracer or a t-r-f radio receiver.

Material Required:

2 CK722 transistors (or equivalent)
2 antenna coils (with ferrite cores)
4 2-μf electrolytic capacitors
1 0.01-μf capacitor
1 1,000-ohm resistor (½ watt)
2 2,700-ohm resistors (½ watt)
2 10,000-ohm resistors (½ watt)
2 22,000-ohm resistors (½ watt)
1 2,200-ohm resistor (½ watt)
1 interstage transformer
1 0.0015-μf capacitor
1 1N34-A or equivalent germanium crystal diode.
1 4.5-volt battery
1 15-volt battery
1 speaker and output transformer or earphone
50 ft of antenna wire
1 two-section, 365-$\mu\mu$f midget variable tuning capacitor

Test Equipment: None

Procedure:

1. Wire the circuit of Fig. 16. Earphones may be substituted for the loudspeaker and its output transformer.

2. Connect a short length of wire to the input capacitor and another length of wire to ground. This system may then be employed as a signal tracer in practically any circuit from audio through TV by connecting the ground lead to the chassis of the device being tested and probing with the other lead. This instrument can be used in any application where the well-known vacuum-tube signal tracer can be employed.

Louder signals can be obtained from the transistor tracer by using 15-volt battery.
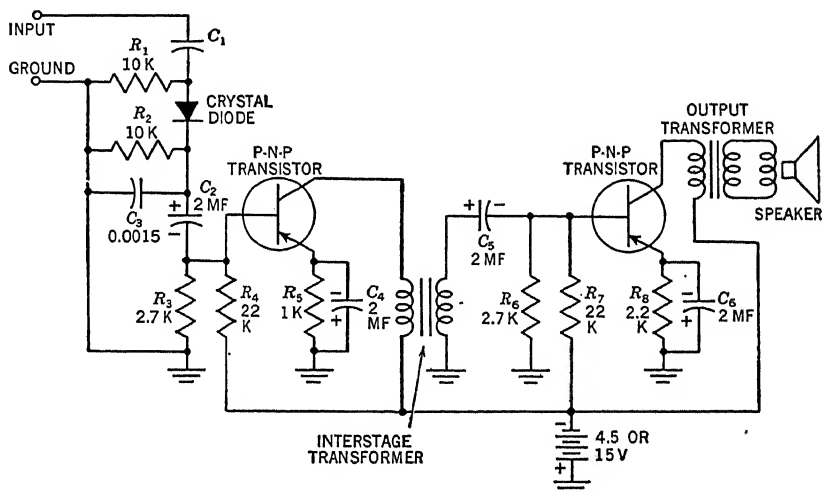
Fig. 16

3. The signal tracer may be tuned by the addition of antenna coils and variable capacitors as shown in Fig. 17. The variable capacitor is a two-gang, 365-$\mu\mu$f capacitor of the midget variety. The coils (L_1 and L_2) are ferrite antenna coils which are coupled together (by close spacing of an inch or less) to provide sufficient selectivity so that local stations may be separated.

A long antenna, 50 ft in length, should be used. The chassis of the transistor receiver should be grounded to a radiator or water pipe. The importance of a good antenna and ground, particularly in an area somewhat remote from high-power broadcast stations, cannot be over-emphasized.

Alignment is perfectly straightforward but should be done carefully in order to realize maximum sensitivity. Any good a-m oscillator or signals from broadcast stations may be used to accomplish the alignment. The parallel trimmers are used to line the setup on the high-fre-

quency end and the coil slugs on the low-frequency end. As is usual in such alignments, peaking is carried out aurally, although an output meter may be placed across the speaker voice coil and the circuits tuned for a meter peak.
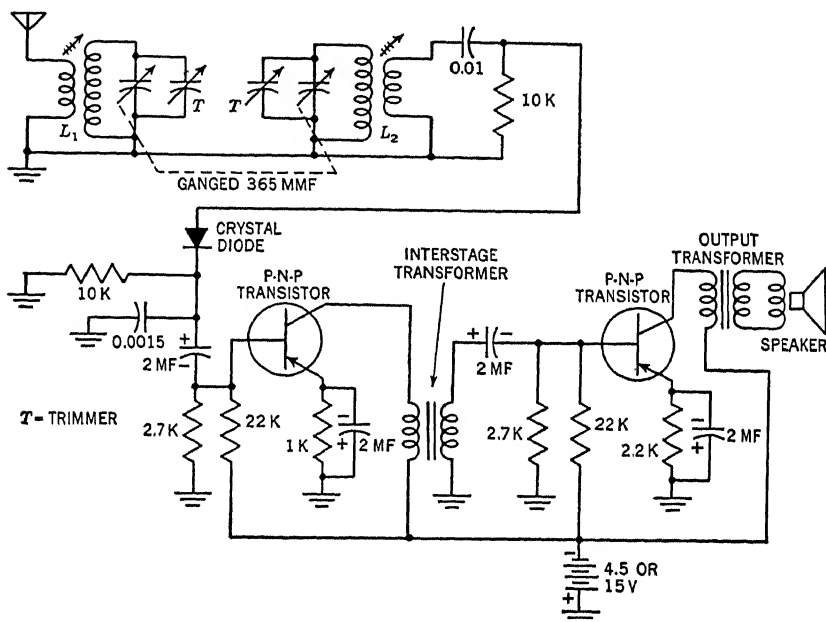
FIG. 17

Conclusions:

1. The transistor amplifier may be converted to a signal tracer by the addition of a germanium diode.

2. Tuning the signal tracer converts it to a t-r-f receiver.

EXPERIMENT 9

Relaxation Oscillator

Object: To analyze the mode of operation and the waveforms in a relaxation oscillator.

Material Required:

2 CK722 transistors (or equivalent)
4 47,000-ohm resistors (¼ watt)

4 10,000-ohm resistors (¼ watt)

2 0.01-μf capacitors

3 2-μf electrolytic capacitors

1 0.0015-μf capacitor

1 4.5-volt battery

Test Equipment:

1 oscilloscope

Procedure:

1. Wire the circuit of Fig. 18.

2. When connected, the circuit will oscillate, producing the non-symmetrical waveforms shown in Fig. 19.
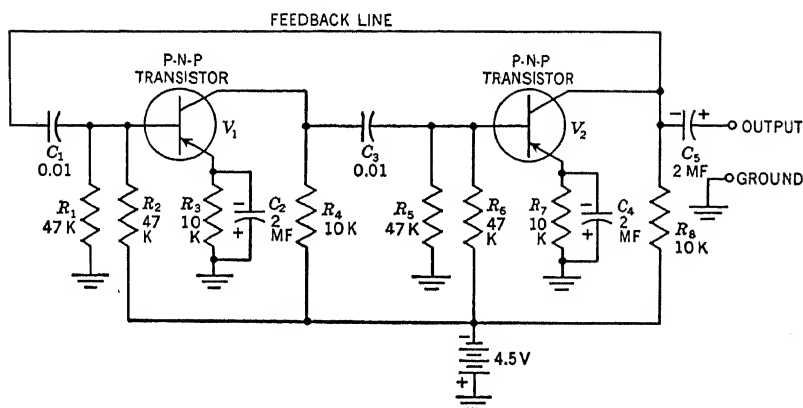
FIG. 18

3. When observing waveforms with an oscilloscope, it is suggested that external synchronization be used. This may be accomplished by attaching a 0.0015-μf capacitor in series with a lead from the *external sync* terminal of the oscilloscope. The other end of this lead should be connected to the collector of transistor 2. The vertical input probe of the oscilloscope may be used for observing the voltage waveform at various points in the circuit. If external synchronization is not used, the waveform will shift as the vertical lead is moved from one point to another.

4. To analyze the operation of the circuit, let us assume that the base of V_1 goes momentarily positive. This decreases the collector current in V_1, causing the voltage at the collector (and the top end of R_4) to become more negative than it was before. This applies a negative

voltage to the base of V_2. Since this acts to increase the forward bias between base and emitter of V_2, the collector current of V_2 will increase and the voltage at the collector will become less negative or more positive. This signal makes the base of V_1 go more positive, thereby aiding the initial positive signal. This is the fundamental requirement of oscillation—positive feedback with a gain greater than 1.

The build-up will continue with the current through V_1 decreasing and the current through V_2 increasing until V_1 is cut off. When the latter condition is reached, the base of V_2 no longer receives any driving signal from the collector of V_1 and the current through V_2 starts decreasing. This brings a negative signal to the base of V_1, gradually bringing this transistor out of cutoff. When V_1 starts conducting, the
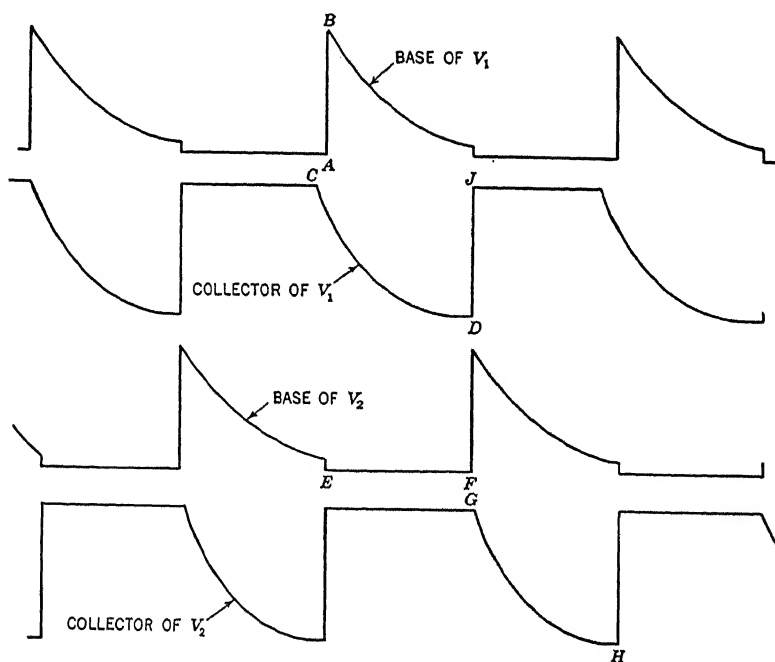
FIG. 19

base of V_2 receives a positive-going signal from V_1 and its current is further decreased. Through this process, the current is built up in V_1 and reduced in V_2 until V_2 becomes nonconducting. In this fashion, control is passed back and forth between V_1 and V_2.

5. Waveform analysis: As the base of V_1 goes positive (points A and B of Fig. 19), it cuts off its collector current. Capacitor C_3 therefore

starts charging through resistors R_4 and R_5. The charging is shown by points C and D. Since capacitor C_2 is charging at a constant rate, the voltage at the base of V_2 is maintained fairly constant (points E and F). When the charging of capacitor C_3 starts to round off slightly (approaching time-constant value), the base voltage of V_2 starts to decrease (go less negative, point F). This causes the collector of V_2 to go more negative (points G and H). When the collector of V_2 goes more negative, it drives the base of V_1 negative, which in turn makes the collector of V_1 go positive (see points D and J). The action is now the same as described previously for the base of V_1.

6. The frequency of oscillation may be changed by varying the coupling capacitors. The frequency may also be altered by varying the base resistors, but this may prove to be somewhat difficult as it will result in a change in the d-c base voltages.

7. By placing a potentiometer in the lead between the collector of V_2 and C_1, a square-wave output may be obtained.

Conclusions:

1. A transistor multivibrator is feasible.

2. The frequency of oscillation is determined by the time constant of the RC circuits. In the circuit shown, it is easier to vary the frequency by varying the coupling capacitors than the resistors.

3. Square and saw-tooth waves can be developed by this oscillator.

EXPERIMENT 10

Blocking Oscillator and Saw-tooth Generator

Object: To study a transistor blocking oscillator and saw-tooth generator.

Material Required:

  1 CK722 transistor (or equivalent)
  2 47,000-ohm resistors (¼ watt)
  1 10,000-ohm resistor (¼ watt)
  1 0.1-μf capacitor
  1 transformer (use interstage transformer)
  1 4.5-volt battery

Test Equipment:

  1 oscilloscope

Procedure:

1. Wire the circuit of Fig. 20.
2. Observe the waveforms at the base, collector, and secondary of the transformer. (Use external synchronization from the secondary of the transformer as described in Experiment 9.)
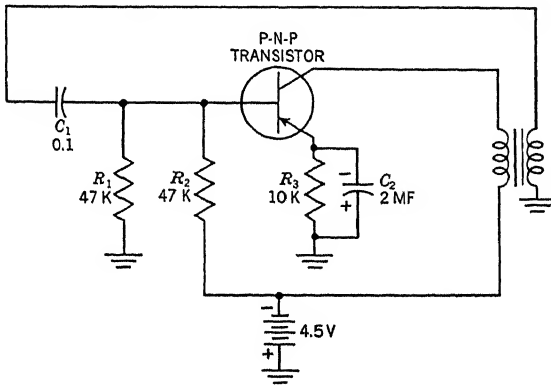
FIG. 20

3. To analyze the operation, at point A (Fig. 21) the base started to go negative, and this drives the collector from point B to point C. At point C the collector current can no longer increase. This removes the feedback which the transformer has been supplying to the base. The base, however, does not reach its most negative point until capacitor C_1 has been fully charged. Once the charging rate of C_1 ceases, the voltage across the base resistor R_1 starts to drop, becoming less
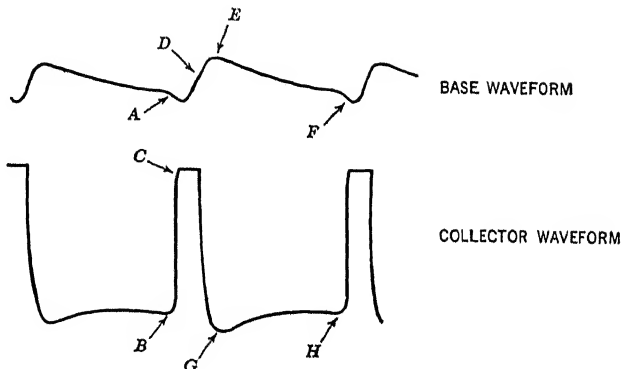
FIG. 21

negative, or more positive. This drives the collector more negative, which, because of the phase reversal of the transformer, causes the base to go more positive (point D). The gradual slope in the base and collector curves (points E and F and G and H, respectively) is the time constant of the capacitor and resistor.

4. If a capacitor is now placed from the collector to ground, a saw-tooth wave will be obtained. Note the similarity between this and the blocking oscillator used in a television set. The frequency may be changed by varying C_1 or R_1.

5. It is suggested that two 10,000-ohm resistors be placed in parallel across the green and black leads of the transformer in waveform experiments. This will eliminate any transformer ringing, if present. By changing the value of this loading resistor you will see how various waveforms may be developed.

Conclusions:

1. A transistor may be employed as a blocking oscillator.

2. The addition of a capacitor from the collector to ground converts the blocking oscillator to a saw-tooth wave generator.

3. As in similar vacuum-tube circuits, the frequency of oscillation is determined by the time constant of the circuit.

EXPERIMENT 11

A Transistor Colpitts Oscillator

Object: To construct a variable-frequency Colpitts r-f oscillator.

Material Required:

    1 CK722 transistor (or equivalent)
    2 0.01-μf capacitors
    2 47-$\mu\mu$f capacitors
    1 10,000-ohm resistor (¼ watt)
    1 coil*
    2 47,000-ohm resistors (¼ watt)
    1 4.5-volt battery

Test Equipment:

    Oscilloscope or radio receiver

   * This may be one of the antenna coils of Experiment 8, using the larger winding. The smaller winding is left unconnected. Or a ferrite-core antenna coil possessing a single winding may be employed.

Procedure:

1. Wire the circuit of Fig. 22.

2. Oscillation should be observed by connecting the vertical lead from the oscilloscope to the collector output capacitor C_4. The other lead from the oscilloscope goes to ground.

3. Vary the frequency of oscillation by varying the slug in the coil. The frequency can also be varied by varying the capacitors C_2 and/or C_3.
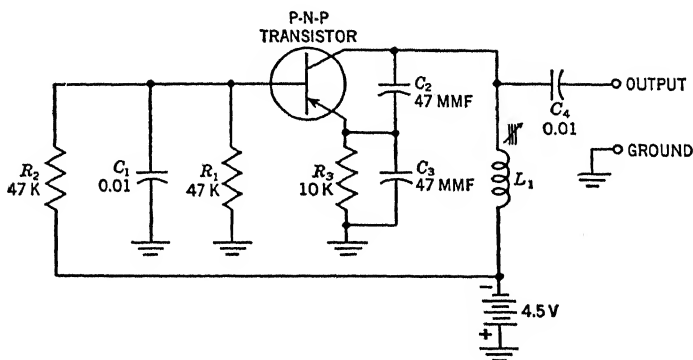
Fig. 22

4. Touch the vertical lead of the oscilloscope, and note the change in oscillator frequency. This is because there is no intervening buffer stage.

5. The frequency of oscillation will probably not go much beyond 1 or 2 Mc with the transistor specified. However, with a transistor designed for high-frequency operation, much higher frequencies could be obtained.

6. Check the amplitude of oscillations as the frequency is raised.

7. Try to reach the highest operating frequency by continually reducing the inductance of the tuning coil. Check the value of this frequency with the two transistors you have.

Conclusions:

1. A Colpitts oscillator can be readily formed with a transistor.

2. The circuit is quite sensitive to "hand-capacitance" effects.

3. Oscillations tend to become weaker as the frequency is raised.

4. The highest operating frequency will tend to vary among similar transistors.

EXPERIMENT 12

Colpitts Oscillator and Buffer Using a Grounded-collector Connection

Object: To construct a buffer Colpitts oscillator arrangement.

Material Required:

2 CK722 transistors (or equivalent)
2 0.01-μf capacitors
2 47-$\mu\mu$f capacitors
1 coil, as in Experiment 11
4 47,000-ohm resistors
2 10,000-ohm resistors
1 4.5-volt battery

Test Equipment:

1 oscilloscope or radio receiver

Procedure:

1. Wire the circuit shown in Fig. 23.
2. The output is taken here from the emitter of the second transistor.
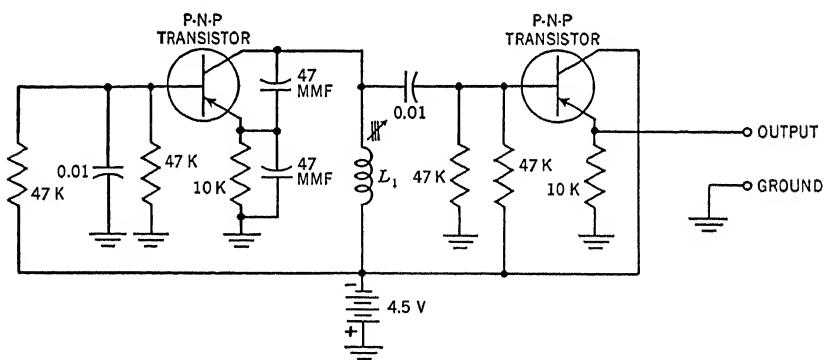
FIG. 23

To observe the waveform of the generated signal, connect the vertical input lead of an oscilloscope to the output terminal. Use a capacitor in series with the oscilloscope lead.

3. Observe the frequency of the waveform and then touch the output lead. The level of the signal may decrease, but its frequency remains essentially unchanged.

4. The grounded-collector stage acts very much as a vacuum-tube

grounded-plate (i.e., cathode-follower) circuit. There is no gain through the grounded-collector circuit, but there is a definite buffer action. As the base of V_2 goes more positive, it decreases the emitter current, which makes the emitter less negative or more positive. The base and emitter voltages are therefore in phase.

Conclusions:

1. It is desirable to employ a buffer stage when operating transistor oscillators that may be subject to varying load conditions. The buffer here is a grounded-collector circuit, but grounded-emitter and grounded-base amplifiers are suitable also. The reader may, if he wishes, construct a Colpitts oscillator with each of the other two types of buffer stages and note which provides the most stable arrangement.

EXPERIMENT 13

Transistor Characteristic Curves *

Object: To obtain the characteristic curves of transistors on the screen of an oscilloscope.

Material Required:

1 CK722 transistor (or equivalent)
1 100-ohm resistors (½ watt)
1 25-ma selenium rectifier
1 6-volt filament transformer (1-amp rating)
1 1.5-volt battery
1 50,000-ohm potentiometer

Test Equipment:

1 oscilloscope
1 vacuum-tube voltmeter or voltmeter

Procedure:

1. Wire the circuit shown in Fig. 24. The lead marked "Hor. Input" is connected to the horizontal terminals of the oscilloscope. The purpose of this connection is to provide a horizontal sweep which is directly proportional to variations in collector voltage. The voltage across R_2 is applied to the vertical input terminals of the oscilloscope, giving a vertical deflection which is directly proportional to the varia-

* W. Philbrook, Obtaining Transistor Characteristic Curves, *Radio & Television News,* September, 1953.

tions in collector current. In this way, we obtain a collector-voltage, collector-current characteristic curve. Note that the internal sweep of the oscilloscope is not used; the horizontal amplifier is switched to "Hor. Input."
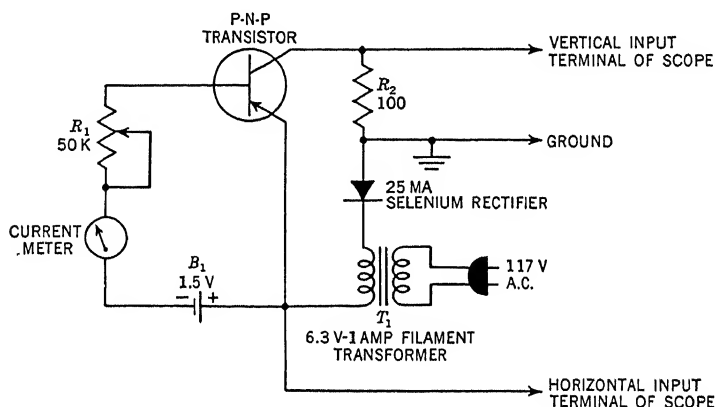
FIG. 24

2. The transistor is connected in Fig. 24 as a grounded-emitter amplifier. With this arrangement, a series of curves are desired for different base currents.* To start, disconnect R_1, making the base current zero. Then, the vertical-gain and horizontal-gain controls of the oscilloscope are adjusted until the desired image size is obtained (see

FIG. 25. Form of a single characteristic curve of a transistor.
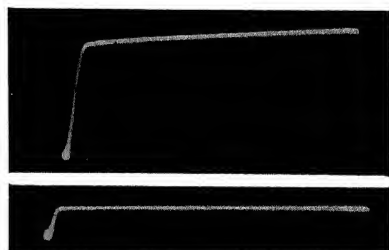
FIG. 26. Characteristic curves obtained with base current (above) of 100 μa and (below) of 20 μa.

Fig. 25). (Do not advance the vertical-gain control too far. The curve obtained when the base current is zero possesses the lowest vertical amplitude. If this curve is made too high, some of the curves to follow will fall beyond the top of the screen.)

* Refer back to Chap. 3, where typical transistor characteristic curves are shown.

3. For each different value of base current, a different characteristic curve is obtained (see Fig. 26). The base current is varied by adjusting potentiometer R_1.

If desired, a transparent scale can be placed over the scope screen and the vertical-gain and horizontal-gain controls adjusted for a known amount of gain. Here is how this is done. Apply a known a-c voltage first to the vertical-input and then to the horizontal-input terminals of the scope and adjust the respective vertical-gain and horizontal-gain controls for a given deflection. For example, an a-c voltage having a peak-to-peak amplitude of 6 volts is applied to the horizontal-input terminals of the scope and the horizontal-gain control adjusted for a deflection of 3 in. The horizontal sensitivity then becomes equal to 2 volts per in. This enables you to measure the collector voltage at any point on a traced-out curve by measuring its distance horizontally along the screen.

For the vertical-input terminals, a smaller voltage, say 0.6 volt peak to peak, is recommended. Then, if the vertical-gain control is adjusted for a deflection of 3 in., the vertical sensitivity becomes 0.2 volt per in. Since the vertical axis of the curves represents current, these voltage values must be converted into equivalent current values. This is readily accomplished, since whatever voltage is applied to the vertical-input terminals of the scope

Fig. 27. Family of collector current versus collector voltage curves for Raytheon CK722 at base currents of 25, 50, 150, and 200 μa, respectively (bottom to top).

must come from the 100-ohm resistor of Fig. 24. Thus, if the transparent scale (over the scope screen) indicates a vertical amplitude of 0.4 volt, then

$$E = IR$$
$$0.4 = I \times 100$$
$$I = \frac{0.4}{100} = 0.004 \text{ amp} = 4 \text{ ma}$$

This is the collector current at the point where the above 0.4-volt amplitude was measured.

Note that once the oscilloscope gain controls are set, they are not touched again, otherwise the calibration is disturbed.

4. The circuit shown in Fig. 24 is for a PNP transistor. To obtain the characteristic curve for an NPN transistor, reverse the connec-

tions to battery B_1 and to the selenium rectifier. The same arrangement may also be employed for point-contact transistors. Again, careful attention must be given to B_1 polarity.

5. To obtain the characteristic curves for a grounded-base arrangement, the connections to the base and emitter of Fig. 24 would be interchanged. Battery polarity, too, would be altered accordingly. Then the curve for a number of emitter current values would be obtained.

6. One curve of a family will be obtained for one value of base (or emitter) current. To obtain a composite or family group of curves, a series of successive photos would have to be taken (see Fig. 27).

7. If greater changes in collector voltage are desired, substitute another transformer for T_1 which will provide a greater secondary voltage. For example, a 12.6- or a 25-volt transformer may be used here.

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TRANSISTOR DATA TABLES

The following six tables, which are being reproduced through the courtesy of *Electronics* magazine,* present the characteristic data of practically all those transistors which were commercially available at the time this book was published. Table 1 contains a listing of the low-frequency low-power triode junction transistors. The majority are utilized in hearing aids, audio systems, low-power control systems, and low-speed computing circuits. Present units are available in the PNP and NPN fused germanium, the NPN grown germanium, and NPN grown silicon types. Of the fused type of transistor, the PNP is more available commercially and consequently has found a wider range of applications. The NPN fused type is suitable for complementary symmetry circuitry. The grown silicon type is used for high-temperature and low-I_{co} applications.

The germanium and silicon grown transistors are used in almost the same manner as the fused transistor. Frequently the grown types, owing to their lower value of collector capacitance and higher value of alpha-cutoff, may be employed as high-frequency transistors.

The maximum power ratings on most of the low-power transistors are of the order of 50 mw collector dissipation at room temperature. Some of these units have external heat sinks and are able to dissipate considerably more power.

The rating most commonly employed is the maximum power rating. Maximum current and maximum voltage ratings cannot be achieved simultaneously, because the product of these two ratings usually exceeds maximum rating. The maximum voltage rating is set at a value safely below the collector voltage breakdown value, while the maximum current is selected where β has not decreased to too low a value.

Table 2, high-frequency transistors, includes PNP and NPN fused junction, NPN grown junction, and PNP surface-barrier units. Except for the NPN grown type, which is of either germanium or silicon, all these units use germanium.

The high-power transistor, Table 3, is in most cases the largest of all transistors. One element is attached to the container. In most units the case may be connected to the chassis either directly or through a thin

* S. Schwartz, Transistor Characteristics for Circuit Designers, *Electronics*, January, 1956.

mica spacer. The types used as power transistors are the germanium PNP fused and silicon NPN grown.

Table 4 lists tetrode junction transistors, which are high-frequency triode NPN grown junction transistors with an extra base lead and a narrower base region. The electrical characteristics of the grown junction tetrode transistor are almost identical with the grown triode transistor except for a lower value of base resistance and a higher value of alpha-cutoff frequency.

The point-contact transistor, Table 5, is limited to high-speed switching circuitry. Phototransistor devices, Table 6, are divided into two basic types: the two-lead and three-lead devices. In the two-lead unit, one lead is attached to the base and the other to the collector. The three-lead device has leads going to the emitter, base, and collector, respectively. The two-lead device is used in circuits providing d-c amplification for unmodulated light, while the three-lead device can be used in circuits employing a-c amplification for modulated light.

Abbreviations Used in Tables

α	Current gain	$g\text{-}e$	Grounded emitter	NF	Noise figure
β	Base-current amplification factor	I_b	Base current	r_b	Base resistance
		I_{b2}	Second base current (tetrode)	r_c	Collector resistance
BW	Bandwidth			r_e	Emitter resistance
C_o	Collector capacitance	I_c	Collector current	R_g	Generator resistance
$f\alpha_{co}$	Alpha-cutoff frequency	I_{co}	Collector cutoff current	R_i	Input resistance
				R_L	Load resistance
$g\text{-}b$	Grounded base	I_e	Emitter current	R_o	Output resistance
$g\text{-}c$	Grounded collector	I_{eo}	Emitter cutoff current	V_o	Collector voltage

Table I. Junction Triode

Manufacturer	Type No.	Type	Max Coll Power (mw)	Max Coll Voltage (v)	Max Coll Current (ma)	Max Ambient Temp (degC)	Bias V_c (v)	Bias I_c (ma)	β	r_e (ohms)	r_b (ohms)	r_c (meg)
Amperex Electronic Corp.	OC70	*pnp* fused	25 (45C)	−10	−10	45	−2	0.5	30	39	1,000	1.43
230 Duffy Ave.	OC71	*pnp* fused	25 (45C)	−10	−10	45	−2	3	47	6 5	500	0.625
Hicksville, N. Y.												
CBS-Hytron	2N36	*pnp* fused	50	−20	− 8	50	−6	1	45	30	450	0.95
Danvers, Mass.	2N37	*pnp* fused	50	−20	− 8	50	−6	1	30	30	350	0.55
	2N38	*pnp* fused	50	−20	− 8	50	−6	1	15	25	350	0.5
	HA-1	*pnp* fused	50	−20	− 8	50	−3	0. 5	40	24	700	1.7
	HA-2	*pnp* fused	50	−20	− 8	50	−3	0.5	30	35	350	0.8
	HA-3	*pnp* fused	50	−20	− 8	50	−3	0 5	30	30	450	0.6
	HC-1	*pnp* fused	50	−20	− 8	50	−6	1	45	30	450	0.95
Germanium Prod. Corp.	NPN-3/	*npn* grown	50 (25C)	35	10	75	4 5 −1		4	25	100	2.0
26 Cornelison Ave.	2N103											
Jersey City, N. J.	RD2517A/	*npn* grown	50 (25C)	30	10	75	4 5 −1		13.3	25	100	3.0
	2N97											
	RD2518A/	*npn* grown	50 (25C)	40	10	85	4.5 −1		13 3	25	100	10.0
	2N97A											
	RD2521A/	*npn* grown	50 (25C)	40	' 10	75	4.5 −1		~40	25	150	5.0
	2N98											
	RD2522A/	*npn* grown	50 (25C)	40	10	85	4.5 −1		40	25	150	10.0
	2N98A											
	RD2523A/	*npn* grown	50 (25C)	40	10	75	4.5 −1		40	25	150	5.0
	2N99											
	RD2525A/	*npn* grown	25 (25C)	25	5	50	4.5 −1		140	25	400	5.0
	2N100											
General Electric Co.	2N43	*pnp* fused	150 (25C)	−45ᵇ	−50	100	−5	1	49	32	400	1.0
Electronics Park	2N44	*pnp* fused	150 (25C)	−45ᵇ	−50	100	−5	1	21.2	26 5	300	1.0
Syracuse, N. Y.	2N45	*pnp* fused	150 (25C)	−45ᵇ	−50	100	−5	1	11.5	20	250	1.0
	2N43A	*pnp* fused	150 (25C)	−45ᵇ	−50	100	−5	1	43.4	15	575	1.43
	2N43A USAF	*pnp* fused	150 (25C)	−45	−50	100	−5	1	43.4	15	575	1.43
	2N76	*pnp* fused	50 (25C)	−20ᵇ	−10	60	−5	1	19	17	300	1.0
General Transistor Corp.	GT-14	*pnp* fused	70 (50C)	−25		85	−4.5	1	28	30	800	1.5
95–18 Sutphin Blvd	GT-20	*pnp* fused	70 (50C)	−25		85			45	30	800	1.5
Jamaica, N. Y.	GT-34	*pnp* fused	70 (50C)	−25		85			15	30	800	1.5
	GT-81	*pnp* fused	70 (50C)	−25		85			65	30	800	1.5
	GT-83	*pnp* fused	70 (50C)	−25		85			45	30	800	1.5
	GT-87	*pnp* fused	70 (50C)	−25		85			28	30	800	1.5
	GT-88	*pnp* fused	70 (50C)	−25		85			65	30	800	1.5
	2N34	*pnp* fused	70 (50C)	−25		85	−4.5	1	40	30	350	2.0
	2N36	*pnp* fused	70 (50C)	−25		85	−4.5	1	45	30	850	2.0
	2N37	*pnp* fused	70 (50C)	−25		85	−4 5	1	30	30	600	2.0
	2N38	*pnp* fused	70 (50C)	−25		85	−4.5	1	15	30	400	2.0
	2N39	*pnp* fused	70 (50C)	−25		85	−4.5	1	45	30	850	2.0
	2N40	*pnp* fused	70 (50C)	−25		85	−4.5	1	28	30	600	2.0
	2N42	*pnp* fused	70 (50C)	−25		85	−4.5	1	13	30	400	2.0
Hughes Aircraft Co	HA5001	*npn* alloyed	500 (25C)	30	100	85	5	1	65 6	16 5	900	2
Culver City, Calif.	HA5002	*npn* alloyed	500 (25C)	20	100	85	5	1	27 5	16	400	1
	HA5003	*npn* alloyed	500 (25C)	20	100	85	5	1	99	26	400	1
Hydro-Aire Inc.	J-1	*pnp* fused	150 (25C)	−40	−10	50	−6	1	34	30	400	1.0
Burbank, Calif.	J-2	*pnp* fused	150 (25C)	−40	−10	50	−6	1	15	30	300	0.7
	J-3	*pnp* fused	150 (25C)	−40	−10	50	−6	1	9	30	300	0.5
	HA-1	*pnp* fused	100 (25C)	−20	−10	50	−6	1	40	30	350	0.75
	CQ-1	*pnp* fused	150 (25C)	−40	−10	50	−6	1	9	30	200	0.5
Nat'l Union Electric	2N39	*pnp* fused	47 (25C)	−27	−12	60	−4.5	1	32.4			1 to 2
350 Scotland Rd.	2N40	*pnp* fused	47 (25C)	−27	−12	60	−4.5	1	15.7–32.4			1 to 2
Orange, N. J.	2N42	*pnp* fused	47 (25C)	−18	−12	60	−4.5	1	9			0.5 to 2
	T34D	*pnp* fused	56 (25C)	−27	−12	70	−4.5	1	32.4	20		1 to 2
	T34E	*pnp* fused	56 (25C)	−27	−12	70	−4.5	1 15.7–32.4		20		1 to 2

Low-power Transistors

Parameters				Grounded-Emitter Connection					Grounded-Base				Grounded-Collector			
f_{aco} (mc)	C_c (μμf)	I_{co} (μa)	NF (db)	I_b (ma)	R_i (ohms)	R_L (ohms)	R_g (ohms)	Gain (db)	R_i (ohms)	R_L (ohms)	R_g (ohms)	Gain (db)	R_i (ohms)	R_L (ohms)	R_g (ohms)	Gain (db)
		−20	28			30,000	500	36								
1.0	49	−10	15		1,000	50,000	matched	42								
1.0	49	−10	12		1,000	50,000	matched	42								
0.7		−10	12		1,200	50,000	matched	43	140	400,000	matched	32.8	500,000	20,000	matched	13.9
0.7		−10	9		1,350	50,000	matched	42.6	130	400,000	matched	33.2	10,000	300	matched	16.2
		−6	22		1,500	20,000	matched	41	70	100,000	matched	31	600,000	20,000	matched	15
		−6	25		500	20,000	matched	36	45	100,000	matched	32	200,000	20,000	matched	10
		−6	20		2,700	20,000	matched	42	110	100,000	matched	30	1,000,000	20,000	matched	16
		−6	12			20,000	1,000	36		200,000	100	28	540,000	10,000	100,000	14
		−6	25		800	20,000	matched	39	50	100,000	matched	32	350,000	20,000	matched	13
		−6	22		1,500	20,000	matched	41	70	100,000	matched	31	600,000	20,000	matched	15
		−6	20		2,700	20,000	matched	42	110	100,000	matched	30	1,000,000	20,000	matched	16
0.6	15	−5	18	−0.03	1,200	30,000	500	40					20,000	500	matched	16
0.8	18	5	16	0.03	1,200	30,000	500	40					20,000	500	matched	16
0.9	15	10	26		480	20,000	500	37	35	100,000	60	30	9,500	500	15,000	12
1.1	17	10	23		970	20,000	500	40	40	100,000	60	30	15,500	500	15,000	14.5
1.3	19	10	20		1,250	20,000	1,250	43	45	100,000	60	31	32,000	500	15,000	17
		3	14			20,000	1,000	32								
		3.5	21			20,000	1,000	29								
		4	26			300	1,000	26								
		−10	25													
		−10	20													
3		1 (25C)	23													
3		1 (25C)	23													
3		1 (25C)	23													
≧8		1 (25C)	23													
		50 (25C)				10,000	500	39								
		−10														
0.8		−10	20			1,000	500	30								
0.8		−10	20			1,000	500	26								
0.8		−20	20			1,000	500	26								
0.5		−10	10			20,000	1,000	36								
0.5		−10	20			20,000	1,000	36								
0.5		−10	20			600	1,000	26								
		−15														
		−10														
		−10	20			30,000	1,000	40								
		−10	20			30,000	1,000	40								
		−15	22			30,000	1,000	36								
		−25	24			30,000	1,000	32								
		−15	20			30,000	1,000	40								
		−15	22			30,000	1,000	37								
		−15	22			30,000	1,000	33								
		−10	25			30,000	1,000	38								
		−10	22			30,000	1,000	39								
		−10	20			30,000	1,000	41								
0.9		−9	14	−0.006		30,000	1,000	33								
0.9		−8	18	−1.5		300		24								
0.7		−10	18	−0.006		30,000	1,000	35								
0.5		−14	21	−0.006		30,000	1,000	27								
0.7		−10	18	−0.006		30,000	1,000	40								
2	17	10	30													
0.95	25	10	30													
0.5		−6			700	50,000	700	39.5	125	300,000	125	31	35,000	1,000	35,000	15
0.5		−6			550	67,000	550	39	125	300,000	125	31	27,000	1,000	27,000	13
0.5		−6			450	85,000	450	37	125	300,000	125	31	20,000	1,000	20,000	11

Table I. Junction Triode Low-

Manufacturer	Type No.	Type	Max Coll Power (mw)	Max Coll Voltage (v)	Max Coll Current (ma)	Max Ambient Temp (degC)	Bias V_c	Bias I_c	β	r_e (ohms)	r_b (ohms)	r_c (meg)
Nat'l Union (cont)	T34F	pnp fused	56 (25C)	−18	−12	70	−4.5	1	9	20		0.5 to 2
Philco Corp.	2N47	pnp fused	50 (25C)	−35	−20		−5	1	39	25	600	1.0
4700 Wissahickon Ave.	2N49	pnp fused	50 (25C)	−35	−20		−5	1	39	25	600	1.0
Philadelphia, Pa.												
RCA	2N104	pnp fused	110 (25C)	−30	50	85	−6	1	44	24.5	750	2.25
Harrison, N. J.	2N77	pnp fused	35 (25C)	−25	15	50	−4	0.7	40	36	560	2.3
Raytheon Mfg Co.	CK721	pnp fused		−15[6]	−10	70	−6	1	45	25	700	2.0
55 Chapel St.	CK722	pnp fused		−22[6]	−10	70	−6	1	22	25	250	2.0
Newton, Mass.	CK725	pnp fused		−12[6]	−10	70	−6	1	90	25	1,500	2.0
	CK727	pnp fused		− 6[6]	−10	70	−1.5	0.5	35	50	500	2.0
	2N63	pnp fused		−22[6]	−10	85	−6	1	22	25	350	2.0
	2N64	pnp fused		−15[6]	−10	85	−6	1	45	25	700	2.0
	2N65	pnp fused		−12[6]	−10	85	−6	1	90	25	1,500	2.0
Sylvania Electric	2N34	pnp fused	50 (25C)	−40	−10		−6	1	40	26	800	2.0
1740 Broadway	2N35	npn fused	50 (25C)	−40	−10		6	−1	40	26	800	2.0
New York, N. Y.												
Texas Instruments	200	npn grown	50 (25C)	30	5	50	5	−1	9	22	150	0.4
6000 Lemmon Ave.	201	npn grown	50 (25C)	30	5	50	5	−1	19	22	170	0.4
Dallas, Texas	202	npn grown	50 (25C)	30	5	50	5	−1	49	35	200	0.4
	206S	npn grown	50 (25C)	30	5	50	2.5	−0.5	35			
	207S	npn grown	50 (25C)	30	5	50	2.5	−0.5	19			
	208S	npn grown	50 (25C)	30	10	50	2.5	−10	19			
	300	pnp fused	50 (25C)	−30	−10	50	−5	1	9		550	0.4
	301	pnp fused	50 (25C)	−30	−10	50	−5	1	19		1,000	0.4
	903	npn grown	150 (25C)	30	10	150	5	−1	9–19	150	500	0.5
	904	npn grown	150 (25C)	30	10	150	5	−1	19–39	150	1,250	0.5
	905	npn grown	150 (25C)	30	10	150	5	−1	≤39	150	2,500	0.5
	904A	npn grown	150 (25C)	30	10	150	5	−1	≤19	150	1,250	0.5
	210	npn grown	50 (25C)	30[7]	5	50	22.5	−2				
	302	pnp fused	50 (25C)	−30	−10	50	−5	1	44			
	350		50 (25C)	−12								
Transitron	2N85	pnp fused	750	−45	−100	100	−12	10	40	2.5	300	0.16
407 Main St.	2N86	pnp fused	750	−60	−100	100	−12	10	20	2.5	300	0.125
Melrose, Mass.	2N87	pnp fused	750	−30	−100	100	−12	10	20	2.5	300	0.125
	2N88	pnp fused	25	−12	−10	85	−1.3	0.5	25	50	1,000	0.5
	2N89	pnp fused	25	−12	−10	85	−1.3	0.5	25	50	1,000	2.0
	2N90	pnp fused	25	−12	−10	85	−1.3	2.5	40	10	600	0.5
	2N91	pnp fused	125	−15	−500	85	−3	30	25	1.5	50	2.0
	2N92	pnp fused	125	−25	−200	85	−3	5	30	5	500	1.0
	2N34	pnp fused	125	−25	−20	100	−6	1	40	18	600	1.0
	2N36	pnp fused	125	−25	−20	100	−6	1	45	18	700	1.0
	2N37	pnp fused	125	−25	−20	100	−6	1	30	20	500	1.0
	2N38	pnp fused	125	−25	−20	100	−6	1	15	20	250	1.0
	2N43	pnp fused	375	−45	−50	100	−6	1	33	20	500	1.0
	2N44	pnp fused	375	−45	−50	100	−6	1	16	20	300	1.0
	2N45	pnp fused	375	−45	−50	100	−6	1	9	20	250	1.0
	2N63	pnp fused	125	−25	−20	100	−6	1	20	20	350	2.0
	2N64	pnp fused	125	−25	−20	100	−6	1	30	20	700	2.0
	2N65	pnp fused	125	−25	−20	100	−6	1	50	18	1,500	2.0
Tung-Sol Electric	DR126	pnp fused	50 (25C)	−10[7]		85	−1.5	0.5	24	26	900	1.5
100 Eighth Ave.	DR128	pnp fused	50 (25C)	−10[7]		85	−1.5	0.5	49	34	1,400	2.0
Newark, N. J.	DR129	pnp fused	50 (25C)	−25[7]		85	−1.5	0.5	32.4	26	1,200	2.0
	DR130	pnp fused	50 (25C)	−25[7]		85	−1.5	0.5	13	20.5	650	1.3
	DR154	pnp fused	50 (25C)	−25[7]		85	−1.5	0.5	124	55	600	1.2
Western Electric	2N27	npn grown	50 (60C)	30	5	85	4.5	−1	19–198	50	700	2.0
120 Broadway	2N28	npn grown	50 (60C)	30	5	85	4.5	−1	5–198	125	1,000	1.0
New York, N. Y.												
Westinghouse	2N54	pnp fused	200 (25C)	−45	−10	60	−6	1	33	25	400	1.0
Box 284	2N55	pnp fused	200 (25C)	−45	−10	60	−6	1	20	20	400	1.0
Elmira, N. Y.	2N56	pnp fused	200 (25C)	−45	−10	60	−6	1	13	5	400	1.0

power Transistors (Continued)

Parameters				Grounded-Emitter Connection					Grounded-Base				Grounded-Collector			
f_{aco} (mc)	C_c (μμf)	I_{co} (μa)	NF (db)	I_b (ma)	R_i (ohms)	R_L (ohms)	R_g (ohms)	Gain (db)	R_i (ohms)	R_L (ohms)	R_g (ohms)	Gain (db)	R_i (ohms)	R_L (ohms)	R_g (ohms)	Gain (db)
		-8	10													
		-8	10													
0.5						30,000	1,000	40								
0.5						30,000	1,000	36								
0.5						30,000	1,000	32								
		-12	12			30,000	1,000	30								
		-12	27			30,000	1,000	30								
						1,200	1,000	35								
0.7		-12				30,000	1,000	40								
0.75	20	5	22	0.25	225	100,000	matched	33	45	250,000	matched	30	2,500	500	matched	7
1.0	19	2	20	0.07	400	100,000	matched	38	35	250,000	matched	32	7,000	500	matched	11
1.0	19	2	15	0.07	400	100,000	matched	38	35	250,000	matched	32	7,000	500	matched	11
2.5	14	2	20	0.025	850	100,000	matched	47	35	250,000	matched	35	20,000	500	matched	15
2.5	14	2	15	0.025	850	100,000	matched	47	35	250,000	matched	35	20,000	500	matched	15
3.5	10	2	15	0.025	850	100,000	matched	47	35	250,000	matched	35	20,000	500	matched	15
5.0	14	2	20	0.007	3,500	100,000	matched	53	45	250,000	matched	35	70,000	500	matched	20
1.0	40	-10	22		1,000	30,000	600	39	60	50,000	100	28	30,000	600	30,000	15
1.0	40	-10	22		700	30,000	600	38	55	50,000	100	28	15,000	600	15,000	12
1.0	40	-10	22		450	30,000	600	36	50	50,000	100	28	7,500	600	7,500	11
1.0	40	-5	10		1,000	30,000	600	39	60	50,000	100	28	30,000	600	30,000	15
1.0	40	-5	30		1,000	30,000	600	39	60	50,000	100	28	30,000	600	30,000	15
1.0	40	-5	18		1,000	30,000	600	38	55	50,000	100	28	15,000	600	15,000	12
0.65		-10	16													
0.65		-10	16													
0.65		-10	16													
0.65		-10	16													
0.70		-10	16													
0.50		-10	16													
1.0		-10	16													
		-15	24													
		-15	24													
		-15	24													
		-15	24													
		-15	24													
		-15	24													
		-15	24													
2.5	15	5														
0.8		12	15													
1.5		10	15													
1.0		-10	11					40								
0.5		-15	22					35								
0.5		-20	33					30								
		-10	20													
0.5		-20	33													
		-10	20			30,000	500	39								
		-10	24			30,000	500	38								
		-20	28			30,000	500	36								
		-10	20			30,000	500	39								
		-10	24			30,000	500	38								

Table II. High-

Manufacturer	Type No.	Type	Max Coll Power (mw)	Max Coll Voltage (v)	Max Coll Current (ma)	Max Ambient Temp (degC)	Storage Temp (deg C)	Typical Small-Signal				
								Bias V_c (v)	I_e (ma)	β	r_e (ohms)	r_b (ohms)
General Electric	2N78	npn rate grown	50 (30C)	15	20	100	100 max	5	−1	27.5		
	2N123	pnp fused	150 (25C)	−15	150		85	−5	1	30–150		
	2N135	pnp alloyed	100 (25C)	−20	−50		85	−5	1	20		
	2N136	pnp alloyed	100 (25C)	−20	−50		85	−5	1	40		
	2N137	pnp alloyed	100 (25C)	−10	−50		85	−5	1	60		
Germanium Prod.	RD2523A (2N99)	npn grown	50 (25C)	40	10	75		5	−1	40	25	150
	RD2525A (2N100)	npn grown	25 (25C)	25	5	50		5	−1	100	25	400
	RD2521A (2N98)	npn grown	50 (25C)	40	10	75		5	−1	40	25	150
	RD2517A	npn grown	50 (25C)	30	10	75		5	−1	13	25	100
Hydro-Aire	HF-1	pnp fused	35 (25C)	−15	−5	55		−4.5	1	25	30	500
	IF-1	pnp fused	35 (25C)	−15	−5	55		−4.5	1	20	30	500
Philco	SB-100	surface barrier	10 (40C)	−4.5	−5		−55 to 85	−3	0.5	19	50	
Raytheon	CK-760	pnp fused		−6³	−5		−55 to 85	−6	1	45	22	70
	CK-761	pnp fused		−6³	−5		−55 to 85	−6	1	50	22	70
	CK-762	pnp fused		−6³	−5		−55 to 85	−6	1	60	22	70
Sylvania	2N94	npn alloyed	50 (25C)	20	10		−55 to 85	6	−0.5	30	52	500
	2N94A	npn alloyed	50 (25C)	20	10		−55 to 85	6	−0.5	30	52	500
Texas Inst.	220	npn grown	50 (25C)	30	5	50		22.5				
	221	npn grown	50 (25C)	30	5	50		22.5				
	222	npn grown	50 (25C)	30	5	50		22.5				
	223	npn grown	50 (25C)	30	5	50		22 5				
	904A	npn grown	150 (25C)	30	10	150		5	−1	≥19	150	1,250
	224–1											
	2											
	3											
	4											
	5											
	225–1											
	2											
	3											
	4											
	5											
	226–1											
	2											
	3											
	4											
	5											
	227–1											
	2											
	3											
	4											
	5											
Tung-Sol	DR-155	pnp fused²	50 (25C)	−10		85	−55 to 85	−1.5	0 5	32		
	2N112	pnp fused	50 (25C)	−10	−8	85	−55 to 85	−6	1	32	31	110
	2N113	pnp fused	50 (25C)	−10	−8	85	−55 to 85	−6	1	32	31	110
Western Electric	2N27	npn grown	50 (60C)	30	5	85		4 5	−1	20–198	50	700

frequency Transistors

Low-Frequency Parameters						H-F Parameters	High-Frequency Circuit Conditions					High-Speed Switching Characteristics			
r_c (meg)	f_{aco} (mc)	C_c ($\mu\mu f$)	I_{co} (μa)	I_{eo} (μa)	NF (db)	$r_b C_c$ ($\mu\mu$ sec)	Application	R_i (ohms)	R_o (ohms)	Power Gain (db)	Circuit	Rise Time (μsec)	Fall Time (μsec)	Reverse Emitter Voltage (v)	Circuit
	5.5	6	1		14		r-f amp	1,000	6,000	20					
							i-f amp	1,500	10,000	30					
	7.5	14	−2	5	10	1,000	switching					0.1	0.2	5	
	4.5	14	5				r-f/i-f amp			29					
	6 5	14	5				"			31					
	10	14	5				"			33					
5.0	3.5	10	2		15		i-f amp unneut	500	10,000	22		<0.2	<0.3		
5.0	5.0	14	2		20		"	750	10,000	23		<0.2	<0.3		
5.0	2.0	14	2		20		"	500	10,000	22		<0.2	<0.3		
3.0	1.0	19	2		20		"	350	10,000	20		<0.2	<0.3		
1.0	5 0	10	−10												
1.0	2 0	10	−10												
0.4	30 (osc)	2 2	−0 5	0 5		800									
1.0	5	14	−2	2	25	1,000									
1.0	10	14	−2	2	25	1,000									
1.0	20	14	−2	2	25	1,000	i-f (g-b)		80	100,000	25⁴	0.15	0.15	≥0	
2.0	3 5	10	3	−3	15	1,000	i-f (g-e)	500	25,000	32⁴					
2.0	6 0	10	3	−3	15	1,200	i-f (g-b)	80	100,000	25⁴		0.1	0.1	≥0	
							i-f (g-e)	800	25,000	35⁴					
							r-f (g-b)	80	15,000	20⁴					
				50			262-kc (g-e) i-f	750	70,000	31					
				50			"	750	70,000	33					
				50			"	750	70,000	35					
				50			262-kc conv	300	60,000	20					
0.5	≥ 8		1				neut 262-kc g-e i-f	600	70,000	26					
										28					
										30					
										32					
										34					
							neut 455-kc g-e i-f	500	50,000	24					
										26					
										28					
										30					
										32					
							neut 262-kc g-b i-f	65	120,000	18					
										20					
										22					
										24					
										26					
							neut 455-kc g-b i-f	65	150,000	18					
										20					
										22					
										24					
										26					
1.0	1.4		−15		28										
1.2	5		−10		28		i-f	600	25,000	32					
1.2	10		−10		28		i-f	600	25,000	33					
2.0	2	17	10												

Table III.

Manufacturer	Type No.	Type	Max Power Output (w)			Max Coll Power (w)	Max Coll Voltage (v) Circuit		Max Coll Current (amp)	f_{aco} (kc)	Small-Signal Bias		
			Class A	Class B (push-pull)	D-C Switch		g-e	g-b			V_c (v)	I_c (ma)	β
Amperex	2N115	pnp fused	1.5	2.5		2(45C)	−12 −6		−1	300			
CBS-Hytron	2-OC72	pnp fused				0.045(45C)	13		0.045	10			
Hydro-Aire	HD-197	pnp fused				0.5(25C)	−40		0.045	150	−10	50	10
Minneapolis-Honeywell	JP-1	pnp fused	0.45	0.9	1.5	0.5(25C)		−45	−0.1	50	−22.5	20	9
Regulator Co. 2753 4th Ave. S Minneapolis, Minn.	H-1	pnp fused	5	10	40	20(21C)	−30	−60	−0.8	20	−2		
	2N57	pnp fused	6	12	48	20(21C)	−30	−60	−1	20	−2		
	H-2	pnp fused	8.5	18	68	20(21C)	−30	−60	−1.4	20	−2		
	H-3	pnp fused	2	4	16	5(21C)	−30	−60	−0.35	20	−2		
	H-4	pnp fused	2	6	16	5(21C)	−30	−60	−0.5	20	−2		
Sylvania	2N68	pnp alloyed	0.75	10		4(25C)		−25	−1.5		−6	50	40
	2N95	npn alloyed	0.75	10		4(25C)		25	1.5		6	−50	40
	2N101	pnp alloyed	electrically identical to 2N68										
	2N102	npn alloyed	electrically identical to 2N95										
Texas Inst.	X-2	npn grown						35	0.075	225	5	−1	9
	951	npn grown silicon		0.45(25C) 0.3(100C) 0.15(150C)		1(25C) 0 5(100C) 0 15(150C)	50		0.06				
	952	npn grown silicon		0.6(25C) 0.4(100C) 0 15(150C)		1(25C) 0.5(100C) 0.15(150C)	80		0.05				
	953	npn grown silicon		1(25C) 0.5(100C) 0.15(150C)		1(25C) 0.5(100C) 0 14(150C)	120		0 04				
Transistor Products 241-251 Crescent Ave. Waltham, Mass.	X-107	pnp fused	1			2(25C)	−30	−60	−1		−24	80	22
	X-120	pnp fused	7.5			15(25C)	−30	−60	−4		−28	360	20
Transitron	2N83	pnp fused	5	15	40	10(25C)	−30	−45	−1	200	−20	100	8
	2N84	pnp fused	5	10	30	10(25C)	−22	−30	−1	200	−20	100	12
Tung-Sol	DR-150	pnp fused		1	3.5	5(25C)		−25	−1	250	−15	10	33
Western Electric	2N66	pnp fused				5(25C)	−40	−60	−0.8	500	−4.5 −40	100 0	45

Power Transistors

| | Low-Frequency Parameters | | | | | Typical Operating Conditions | | | | | | | | | | |
r_e (ohms)	r_b (ohms)	r_c (ohms)	C_c ($\mu\mu$f)	Rise Time (μsec)	I_{co} (μa)	Class & Circuit	Supply Voltage (v)	Coll Current (ma)	Base Current (ma)	Zero Signal Current (ma)	Power Output (w)	Power Gain (db)	Driving Power (mw)	R_c (ohms)	R_L (ohms)	R_g (ohms)
						B(g-e)	-6	-1,280		-5	5[4]	27				
						B(g-e)	-6				0.2[4]	27				
	70	5,000				A		-50				30			5,000	100
2	150	100,000			-500	B(g-b)	-22.5	-40			0.7[4]	20				
				1.5	-8,000	A(g-e)	-28	400	50		5	15	158	20	70	4
						B(g-e)	-28	510		4	10[4]	12	630	100	140	4
				1.2	-8,000	A(g-e)	-28	500	45		6.25	16	156	35	56	4
						B(g-e)	-28	640		4	12.5[4]	13	625	140	128	4
				0.5	-8,000	A(g-e)	-28	600	30		7.5	20	75	40	47	4
						B(g-e)	-28	890		4	17.5[4]	16	440	100	80	4
				1.2	-1,000	A(g-e)	-28	150	15		1.9	16	48	100	187	4
						B(g-e)	-28	220		0.5	4.4[4]	12	278	240	320	4
				0.6	-1,000	A(g-e)	-28	150	10		1.9	21	15	60	187	4
						B(g-e)	-28	318		0.5	6.25[4]	14	250	200	224	4
1	30	100,000	300		-100	A(g-b)	-12	-150			0.6	23		75	100	50
						B(g-e)	-12	-550		-1	5[4]	15		50	12	50
						B(g-c)	-12	-550		-1	5[4]	10		250	12	100
						B(g-b)	-24	-950		-1	10[4]	10		2	24	2
1	30	100,000	300		100	A(g-b)	12	150			0.6	23		75	100	
						B(g-e)	12	550		1	5[4]	15		50	12	
						B(g-c)	12	550		1	5[4]	10		250	12	
						B(g-b)	24	950		1	10[4]	10		2	24	
25	0.75	200,000			25	B(g-b)	22.5	40			0.5[4]	9.5			1,000	
						B(g-b)	22.5	40			0.5	22.7			1,000	
					5	B(g-e)	28	30			0.45(25C)[4] 0.15(150C)	20			1,500	1,000
					6	B(g-e)	45	25			0.6(25C)[4] 0.15(150C)	21			4,000	1,000
					8	B(g-e)	67.5	20			1(25C)[4] 0.15(150C)	23			8,000	1,000
0.85	12	50,000			-120	A(g-b)	-28	-80			1	24	4	1.5	375	
0.65	1	10,000			-200	A(g-b)	-28	-360			5	20	50	0.8	100	
0.3	15	20,000	400	1.5	-100	B(g-e)	-30	-160			2.5[4]	24			600	100
0.3	15	20,000	400	1.5	-100	B(g-e)	-20	-160			2.0[4]	22			400	100
		30,000														
			400		75											
					300											

Table IV. Grown NPN Junction Tetrode Transistors

Manufacturer	Type No.	Max Coll Power (mw)	Max Coll Voltage (v)	Max Coll Current (ma)	Max Base-to-Base Current (ma)	Application	Small-Signal Low-Frequency Parameters						
							Bias		I_{b2} (ma)	α	r_e (ohms)	r_b (ohms)	r_c (megohms)	I_{co} (μa)
							V_c (v)	I_c (ma)						
Germanium Prod.	RDX-302/3N23	50(25C)	30	5	5	video amp, switching 10-mc osc	4.5	1	0	0.95	30	70	2	10
	RDX-301/3N23A	50(25C)	30	5	5	video amp, switching 20-mc osc	4.5	1	0	0.97	30	100	2	10
	RDX-300/3N23B	50(25C)	30	5	5	video amp, switching 35-mc osc 20-mc i-f	4.5	1	0	0.98	30	200	2	10
	RDX-300A/3N23C	50(25C)	30	5	5	video amp, switching 50-mc osc, 20 to 30 mc i-f	4.5	1	0	0.99	30	300	2	10
Texas Inst.	700	50(25C)	30	5	5	low-level, low-freq agc	5	−1	0	0.95	30	1,000	1	10
Western Electric	3N22	30(25C)	12	5	5	video amp, r-f	9	−2	−4.5	0.90	25	100	1	10
							9	−2	0	0.975	25	1,000	1	

Table V. Point-contact Transistors

Manufacturer	Type No	Application	Max Coll Power (mw)	Max Coll Voltage (v)	Max Coll Current (ma)	Max Reverse Emitter Voltage (v)	Max Emitter Current (ma)	Max Emitter Power (mw)	Bias V_c (v)	Bias I_e (ma)	$-\alpha$	r_e (ohms)	r_b (ohms)	r_c (ohms)	f_{aco} (mc)	C_c ($\mu\mu$f)	Nf (db)	I_{co} (μa)	Rise Time (μsec)	Turn Off Time (μsec)	Off I_e (ma)	On V_c (v)	Emitter Rev Resist. (ohms)	α (at max rise time)
Hydro-Aire	A-0	amp. osc	0(25C)	-20	-8				-8	0.3	2	425	200	13,000	3			-1,200						
	A-1	amp. osc	50(25C)	-20	-8				-8	0.3	2	425	200	13,000	2			-1,500						
	A-2	amp. osc	50(25C)	-20	-8				-8	0.3	2	375	175	13,000	1			-2,000						
	A-3	amp. osc	50(25C)	-20	-8				-8	0.3	2	350	150	13,000	0.3			-2,000						
	S-0	switching	50(25C)	-40	-8	-30													0.2		-1	-2	50,000	
	S-1	switching	50(25C)	-40	-8	-30													0.5		-1	-2	50,000	
	S-2	switching	50(25C)	-30	-10	-30													1		-1	-2	50,000	
Sprague Electric Transistor Prod	5A	switching	80(25C)	-50	-8	-50			-10	1	3				5		43		0.12	0.5				
	2A	amp, osc, sw	120(25C)	-50	-8	-50																		
	5C	switching	100(25C)	-50	-8	-50																		
	2D	amp, osc	100(25C)	-50	-8	-50																		
	2E	amplifier	120(25C)	-50	-8	-50																		
	2G	switching	100(25C)	-50	-8	-50																		
	2H	amplifier	50(25C)	-50	-8	-50																		
	2L	switching	50(25C)	-40	-8	-40																		
	2N32	switching	30(35C)	-8.5	-7	-15																		
	2N33	switching	50(25C)	-15	-1	-50																		
	2N50	switching	100(25C)	-50	-8	-50																		
	2N51	sw, osc	120(25C)	-50	-8	-50																		
	2N52	amp, osc	120(25C)	-50	-8	-50																		
	2N53	switching	120(25C)	-50	-8	-50																		
Western Electric	2N21	switching	120(25C)	-100	-60	-100	60	80(25C)	-10	1	2.5	200	90	10,000	2		45	-1.1	0.2	1.3	-1.1	-1	200,000	5
	2N21A	amp, osc, sw	120(25C)	-100	-60	-100	60	80(25C)	-10	1	2.5	200	90	10,000	2		45	-1.1	0.2	1.3	-1.1	-1	200,000	5
	2N110	switching	200(25C)	-100	-75	-100	75	100(25C)	-10	1	2.5	200	90	15,000	1.5			-0.9	0.3	1.3	-0.9	-1	200,000	4
	2N67	h-speed sw	100(25C)	-100	-60	-100	60	60(25C)	-10	1	3	900	500	20,000	20			-0.9	0.02	0.9	-0.9	-0.8	2,000,000	7

Table VI. Phototransistors

Manufacturer	Type No.	Type	Max Coll Voltage (v)	Max Coll Current (ma)	Max Coll Power (mw)	Max dark Current (µa)	Max Ambient Temp. (deg C)	Cutoff Freq. (kc)	Noise (ft-candles)	Sensitivity (µa/ft-candles)
General Transistor	GT-66	fused, 3 lead	12	20	50(25C)	15		750	6×10^{-3}	25
Texas Inst.	800	grown, 2 lead	20	20	50(25C)	250	40	20		35
Transistor Prod.	1N188	grown, 2 lead	100		40(25C)		50		3 to 10 µv	10 µa/millilumen
	1N189	nonrect. 2 lead			30(25C)	20	50			0.08%/ft-candle
	10A	grown, 2 lead	15		100(25C)	500	50		15 to 100µv	4ma for 300 ft-candles
	10B	grown, 2 lead	15		100(25C)	50	50		15 to 100µv	50% for 10 ft-candles
	5B	grown, 2 lead	50		100(25C)	20	50		3 to 10µv	1ma for 300 ft-candles
	5C	grown, 2 lead	50		100(25C)	5	50		3 to 10µv	50% for 40 ft-candles
	11A	nonrect. 2 lead	15		50(25C)	4,000 ohms	50			2,000 ohms for 300 ft-candles
	11B	nonrect. 2 lead	15		50(25C)	4,000 ohms	50			3,000 ohms for 300 ft-candles
	17A	grown, 2 lead							below 1µv	
Western Electric	1N85	grown, 2 lead	90	1	50	20	85	25	2×10^{-4}µa	0.35µa/µw

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